Results and Prospects for $K \to \pi\nu\bar{\nu}$

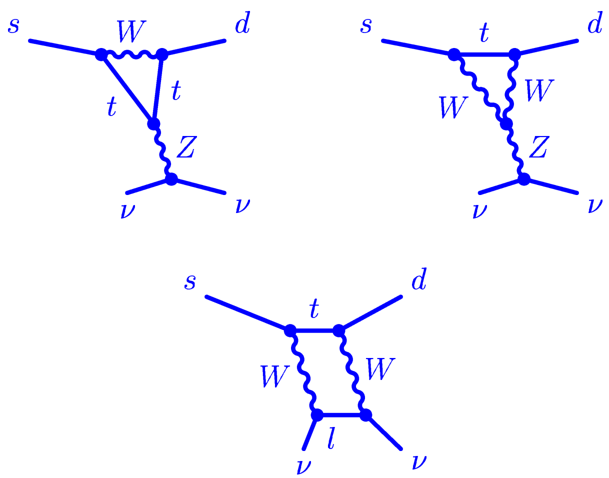
David E. Jaffe, BNL

- Introduction
- $K^+ \to \pi^+\nu\bar{\nu}$: E949 experimental method and results
- $K^0_L \to \pi^0\nu\bar{\nu}$: KOPIO experimental method and prospects
- Summary and outlook

BROOKHAVEN NATIONAL LABORATORY

IPPAP at Virginia Tech

$\mathbf{K \rightarrow \pi\nu\bar{\nu}}$ in the Standard Model and beyond



- Negligible long distance effects (10^{-13})
- Hadronic matrix element via isospin analog $K^+ \rightarrow \pi^0 e^+ \nu$

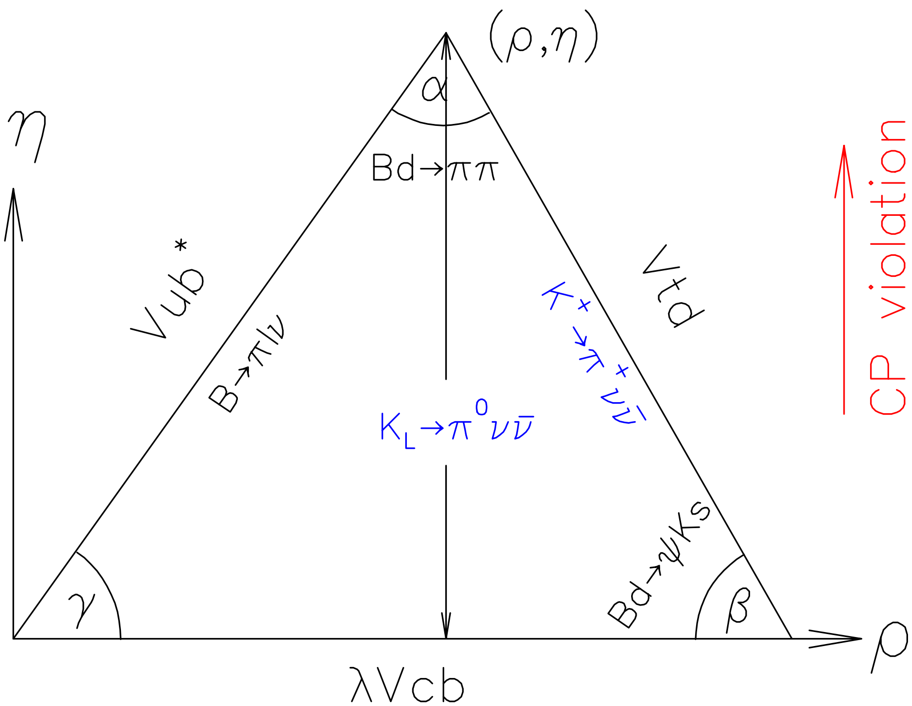
	$\mathcal{B}(K^+ \rightarrow \pi^+\nu\bar{\nu})$	$\mathcal{B}(K^0_L \rightarrow \pi^0\nu\bar{\nu})$
top dep.	$\lvert V^*_{ts}\, V_{td}\rvert$	$Im(V^*_{ts}\, V_{td})$
Msmt[a,b,c]	$(1.57^{+1.75}_{-0.82}) \times 10^{-10}$	$< 5.9 \times 10^{-7}$ $< 4.4 \times \mathcal{B}(K^+ \rightarrow \pi^+\nu\bar{\nu}$
SM[d]	$(0.77 \pm 0.11) \times 10^{-10}$	$(0.26 \pm 0.05) \times 10^{-10}$
SM Uncert.[f]	7%	2%
MFV[g]	1.91×10^{-10}	0.99×10^{-10}
EZP[h]	$(0.75 \pm 0.21) \times 10^{-10}$	$(3.1 \pm 1.0) \times 10^{-10}$

Limits are at 90% CL.

References

(a) PRL **88** (2002) 041803
(b) PR **D61** (2000) 072006
(c) PL **B398** (1997) 163
(d) `hep-ph/0307014`
(e) `hep-ph/0212321`
(f) `hep-ph/0101336`
(g) Minimal Flavor Violation, Buras, `hep-ph/0310208`
(h) Enhanced Z^0 Penquins, Buras *et al.*, `hep-ph/040211`

"Golden" modes and the CKM unitarity triangle



Process	Expts
$\mathcal{B}(\mathrm{K}^0_\mathrm{L} \to \pi^0\nu\bar{\nu})$	KOPIO, E391a
$\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu})$	E787/E949
$\mathcal{A}(B \to J/\psi \mathrm{K}^0_\mathrm{S}; t)$	BaBar, Belle
$\Delta m_s/\Delta m_d$	CDF, D0

Comparison of $|\mathrm{V}_{\mathrm{td}}|$ from $\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu})$ and $\Delta m_s/\Delta m_d$ is an important test of the SM.

Comparison of $\sin 2\beta$ from $\mathcal{B}(\mathrm{K}^0_\mathrm{L} \to \pi^0\nu\bar{\nu})/\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu})$ and $\mathcal{A}(B \to J/\psi \mathrm{K}^0_\mathrm{S}; t)$ is perhaps **the** definitive test of CP violation in the SM.

Rare K decays and new physics (ref:G.Isidori, hep-ph/0301159)

Precision measurements of rare decays:

1. Improve our knowledge of CKM matrix
2. Probe flavor structure of new physics

Rare processes mediated by Flavor Changing Neutral Currents are ideal candidates:

- No SM tree-level contribution
- Strong suppression by CKM hierarchy
- Precisely calculable within SM if dominated by short-distance dynamics

Present CKM fits involve only $\Delta F = 2$ loops and tree level amplitudes.
We know very little about $\Delta F = 1$ FCNC transitions.

Each box corresponds to an independent combination of dimension-6 operators.

Th. error $\lesssim 10\%$

decreasing SM contrib. →

decrea-sing SM contrib. ↓

	$b \to s$ $(\sim\lambda^2)$	$b \to d$ $(\sim\lambda^3)$	$s \to d$ $(\sim\lambda^5)$
$\Delta F=2$ box	ΔM_d $A_{CP}(B_s \to \psi K)$	ΔM_s $A_{CP}(B_s \to \psi\phi)$	ΔM_K ε_K
$\Delta F=1$ 4-quark box	$B_d \to \pi K$, $B_d \to \eta K$, $A_{CP}(B_d \to \phi K)$, ...	$B_d \to \pi\pi$, $B_d \to \rho\pi$, $A_{CP}(B_d \to \pi\pi)$, ...	ε'/ε, $A_{CP}(K \to 3\pi)$, ...
gluon penguin	$B_d \to X_s\gamma$, $B_d \to \pi K$, $A_{CP}(B_d \to \phi K)$, ...	$B_d \to X_d\gamma$, $B_d \to \pi\pi$, $A_{CP}(B_d \to \pi\pi)$, ...	$K_L \to \pi^0 l^+ l^-$, ε'/ε, ...
γ penguin	$B_d \to X_s l^+ l^-$, $B_d \to X_s\gamma$ $B_d \to \pi K$, $B_s \to KK$, ...	$B_d \to X_d l^+ l^-$, $B_d \to X_d\gamma$ $B_d \to \pi\pi$, $B_s \to \pi K$, ...	$K_L \to \pi^0 l^+ l^-$, ε'/ε, ...
Z^0 penguin	$B_d \to X_s l^+ l^-$, $B_s \to \mu^+\mu^-$ $B_d \to \pi K$, $B_s \to KK$, ...	$B_d \to X_d l^+ l^-$, $B_d \to \mu^+\mu^-$ $B_d \to \pi K$, $B_s \to KK$, ...	$K_L \to \pi^0 l^+ l^-$, $K_L \to \pi^0 \nu\nu$ $K^+ \to \pi^+ \nu\nu$, ε'/ε, ...
H^0 penguin	$B_s \to \mu^+\mu^-$	$B_d \to \mu^+\mu^-$	$K_{L,S} \to \mu^+\mu^-$

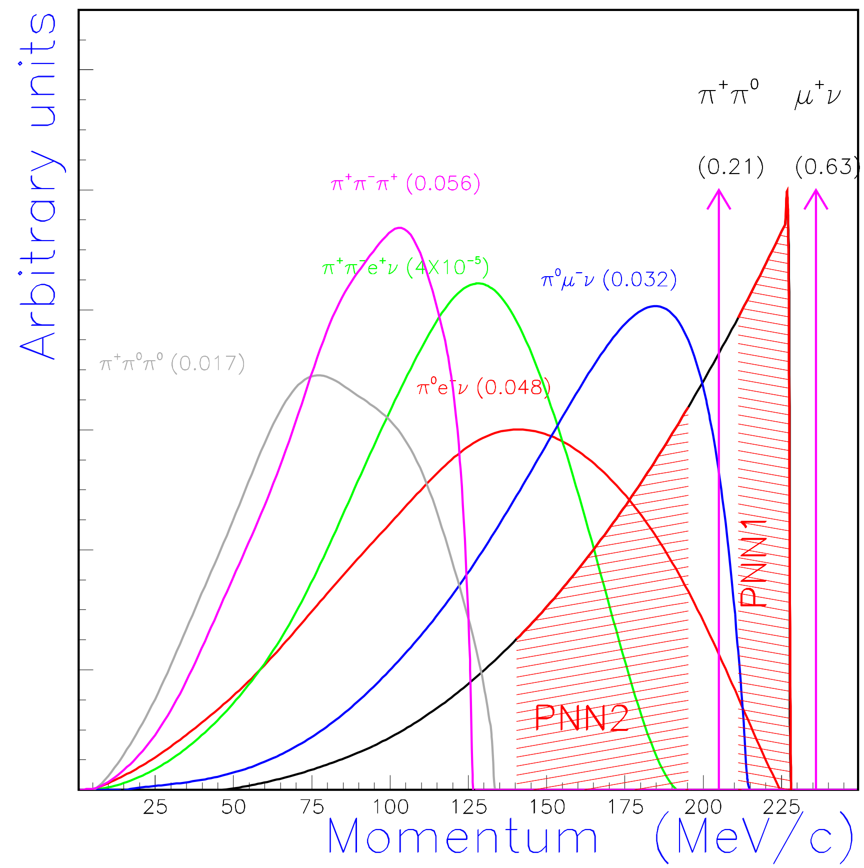
(grey oval) = exp. error $\lesssim 10\%$ (open oval) = exp. error ~ 30-50%

Name	**"PNN2"**	**"PNN1"**
P_π (MeV/c)	[140,195]	[211,229]
Years	1996- 97	1995-98
Stopped K^+	1.7×10^{12}	5.9×10^{12}
Candidates	1	2
Background	1.22 ± 0.24	0.15 ± 0.05
$\mathcal{B}(K^+ \to \pi^+\nu\bar\nu)$	$< 22 \times 10^{-10}$	$(1.57^{+1.75}_{-0.82}) \times 10^{-10}$

E787
$K^+ \to \pi^+\nu\bar\nu$
results

PNN1: PRL **88**, 041803 (2002).

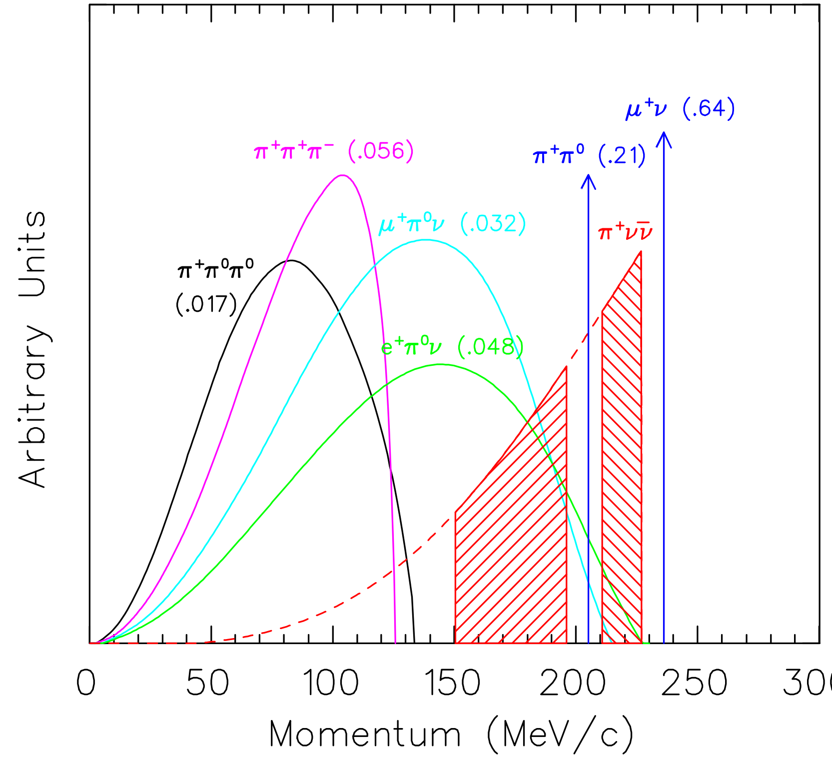
PNN2: Limit at 90%CL is combined result from 1996 (PL **B537**, 211 (2002)) and 1997 (hep-ex/0403034) data.



$K^+ \to \pi^+\nu\bar{\nu}$ and background rates

Process	Rate
$K^+ \to \pi^+\nu\bar{\nu}$	0.77×10^{-10}
$K^+ \to \pi^+\pi^0$	$2113000000.00 \times 10^{-10}$
$K^+ \to \mu^+\nu$	$6343000000.00 \times 10^{-10}$
$K^+ \to \mu^+\nu\gamma$	$55000000.00 \times 10^{-10}$
$K^+ \to \pi^0\mu^+\nu$	$327000000.00 \times 10^{-10}$
CEX	$\sim 46000.00 \times 10^{-10}$
Scattered π^+ beam	$\sim 25000000.00 \times 10^{-10}$

π^+ momentum in K^+ rest fram



CEX $\equiv(K^+n \to K^0X)\times(K^0 \to K^0_L) \times (K^0_L \to \pi^+\ell^-\nu)$

ℓ^- is μ^- or e^-

$K^+n \to K^0X$ rate is empirically determined.

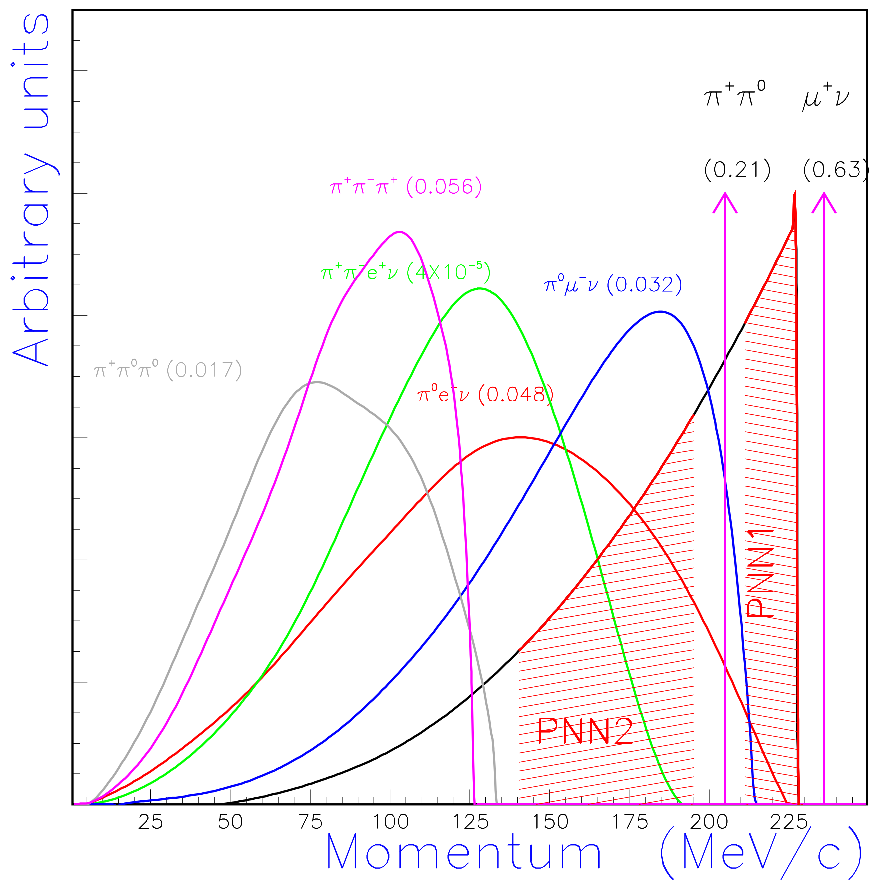
E787 experimental method

Measure everything possible.

- Independent measurements of range(R), energy(E) and momentum(P) of π^+
- Positive identification of incoming K^+ and outgoing π^+
- Veto extra photons and charged particles

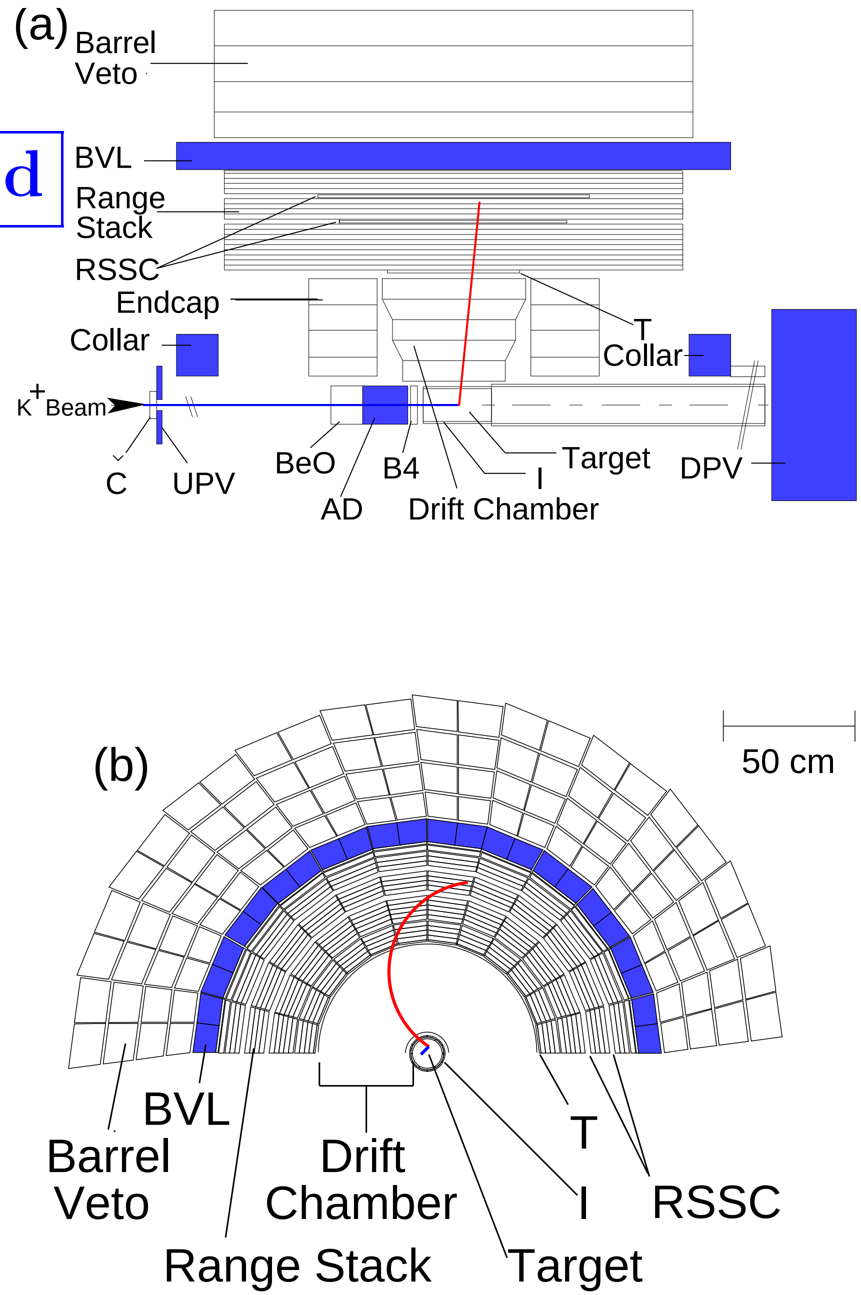
Background must be suppressed by 10^{11}: Bkgd/S(SM) < 0.1

Measure background with data — set cuts based on 1/3 of data and evaluate bkgd with remaining 2/3.



E949 experimental method

- ~ 700 MeV/c K^+ beam
- Stop K^+ in scint. fiber target
- Wait at least 2 ns for K^+ decay
- Measure P in drift chamber
- Measure range R and energy E in target and range stack (RS)
- Stop π^+ in range stack
- Observe $\pi^+ \to \mu^+ \to e^+$ in RS
- Veto photons, charged tracks
- **New/upgraded detector elements**



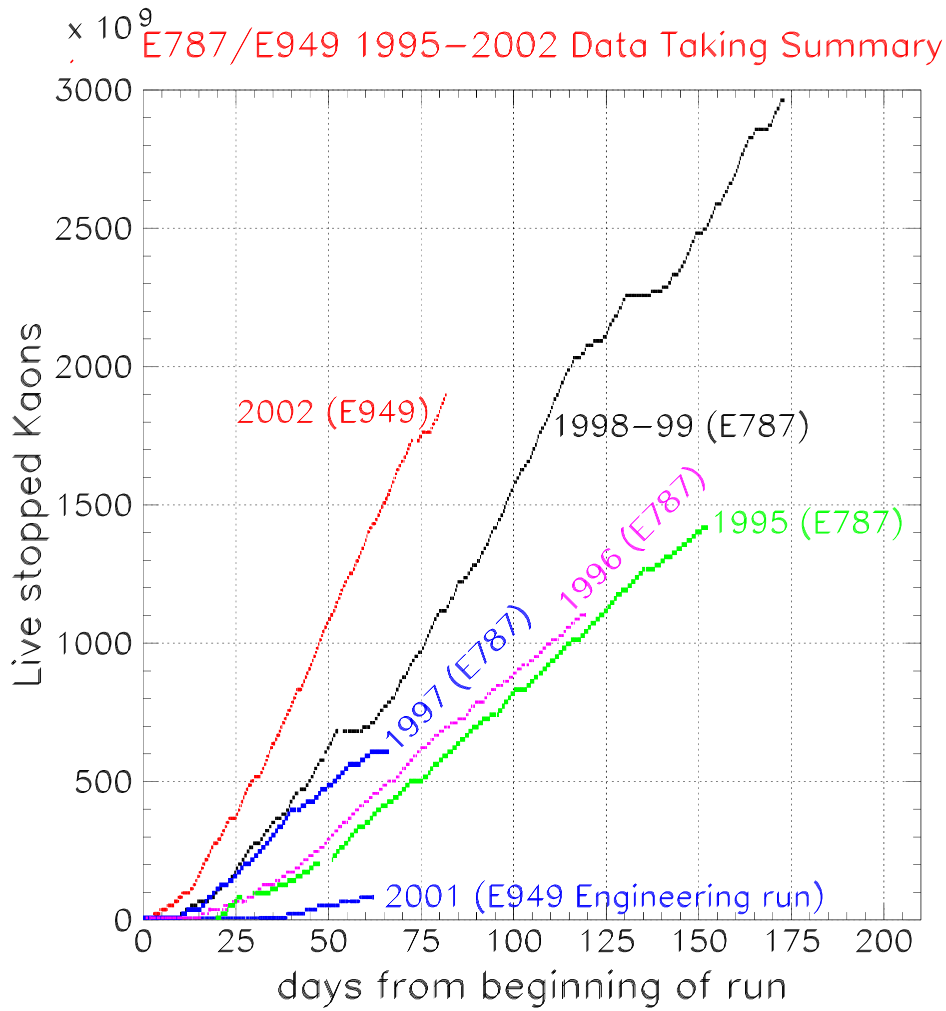
E949 status for 2002 data taking

Upgrades to E787:

- More protons/sec from AGS
- Improved photon veto hermeticity
- Improved tracking and energy resolution
- Higher rate capability due to DAQ and trigger improvements

Not optimal in 2002:

1. Spill duty factor.
2. Proton beam momentum.
3. K/π electrostatic separators.

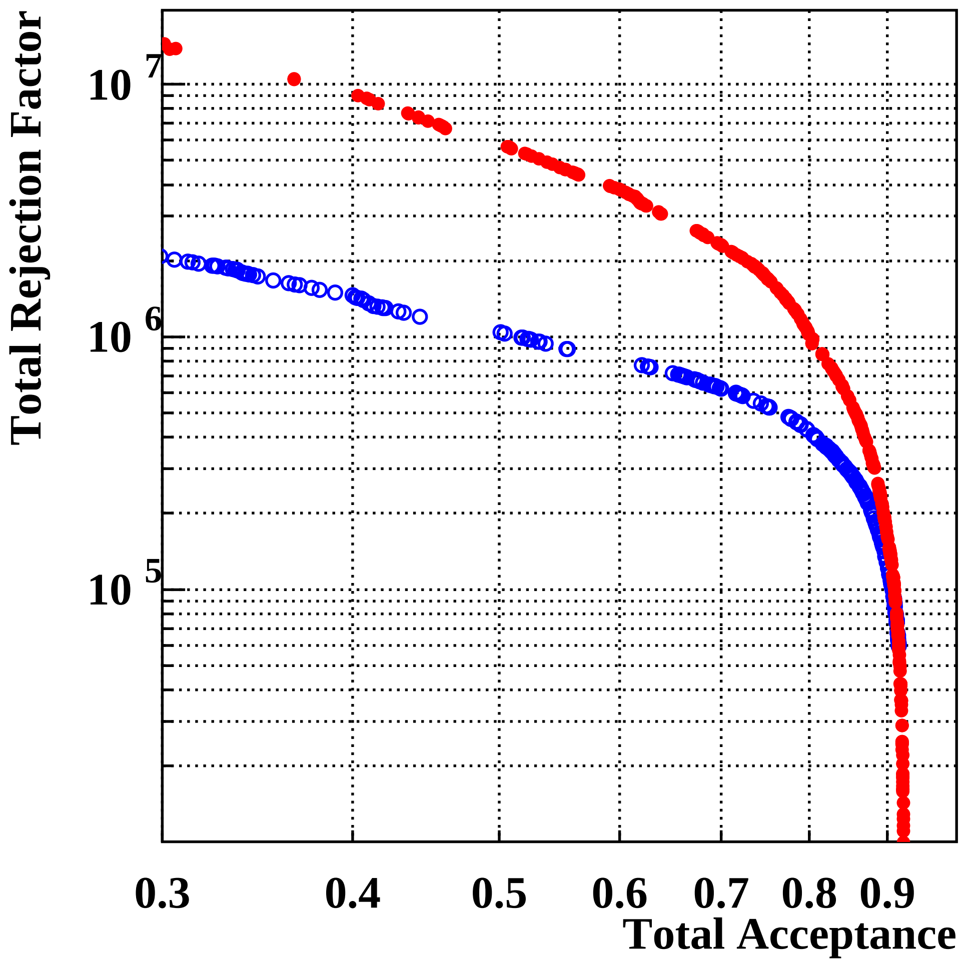


E949: Upgrade of photon veto

Improved photon veto hermeticity.

Figure: background **Rejection** as a function of $K^+ \to \pi^+ \nu \bar{\nu}$ signal **Acceptance** for the photon veto cut for E787 and E949.

$\sim$ 2$\times$ better rejection at nominal **PNN1** acceptance of 80% *or* $\sim$ 5% more acceptance in E949 with same rejection as E787.



E787 and E949 analysis strategy

- **"Blind" analysis. Don't examine signal region until all backgrounds verified.**
- A priori identification of background sources.
- Suppress each background source with at least two independent cuts.
- Backgrounds cannot be reliably simulated: measure with data by inverting cuts and measuring rejection taking any (small) correlations into account.
- To avoid bias, set cuts using 1/3 of data, then measure backgrounds with remaining 2/3 sample.
- Verify background estimates by loosening cuts and comparing observed and predicted rates.
- Use MC to measure geometrical acceptance for $K^+ \to \pi^+ \nu\bar{\nu}$. Verify by measuring $\mathcal{B}(K^+ \to \pi^+\pi^0)$.

E787 and E949 analysis strategy

- "Blind" analysis. Don't examine signal region until all backgrounds verified.
- A priori identification of background sources.
- Suppress each background source with at least two independent cuts.
- Backgrounds cannot be reliably simulated: measure with data by inverting cuts and measuring rejection taking any (small) correlations into account.
- To avoid bias, set cuts using 1/3 of data, then measure backgrounds with remaining 2/3 sample.
- Verify background estimates by loosening cuts and comparing observed and predicted rates.
- Use MC to measure geometrical acceptance for $K^+ \to \pi^+ \nu \bar{\nu}$. Verify by measuring $\mathcal{B}(K^+ \to \pi^+ \pi^0)$.

Background suppression

Source	Suppression method: Kinematics	Particle ID	Veto	Timing
$K^+ \to \mu^+\nu(\gamma)$	$\surd$	$\surd$	$(\surd)$	
$K^+ \to \pi^+\pi^0$	$\surd$		$\surd$	
Scattered beam		$\surd$		$\surd$
CEX			$\surd$	$\surd$

CEX $\equiv K^+n \to K^0p$, $K_L^0 \to \pi^+\ell^-\nu$

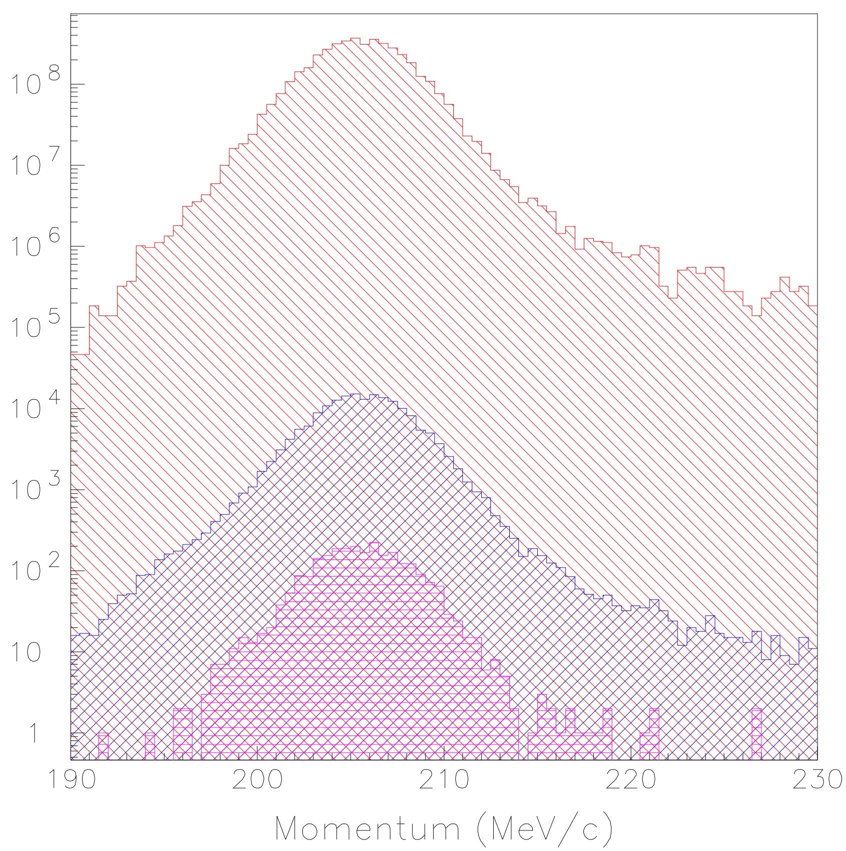
Particle ID includes beam Cherenkov, dE/dx and $\pi \to \mu \to e$ detection

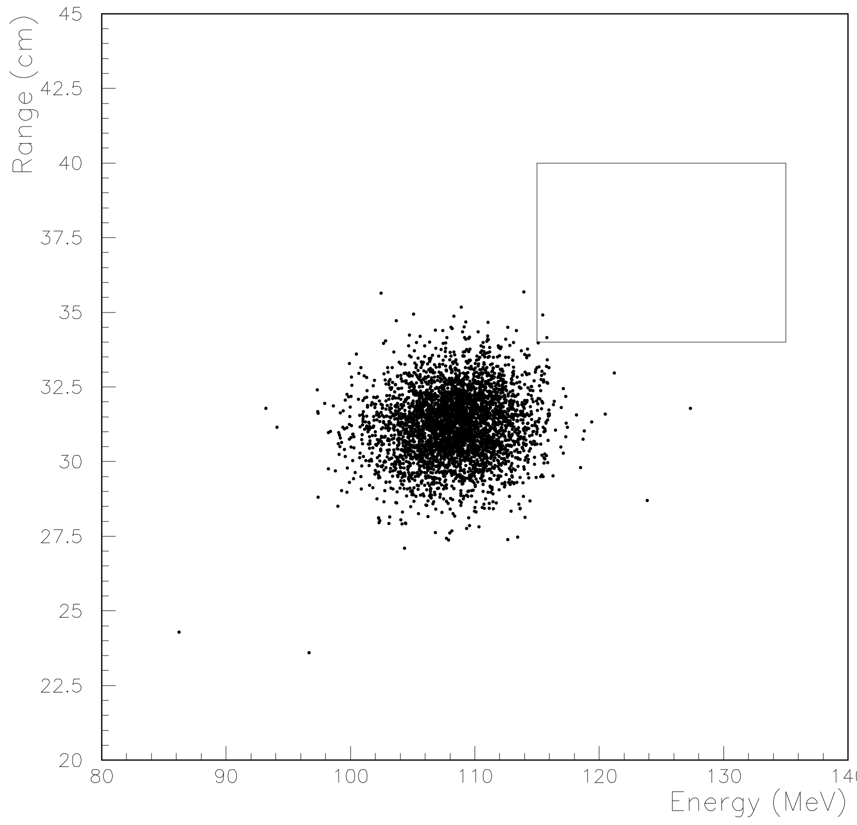
Veto includes both photon and charged particle vetoing

E787 and E949 analysis strategy

- "Blind" analysis. Don't examine signal region until all backgrounds verified.
- A priori identification of background sources.
- Suppress each background source with at least two independent cuts.
- Backgrounds cannot be reliably simulated: measure with data by inverting cuts and measuring rejection taking any (small) correlations into account.
- To avoid bias, set cuts using 1/3 of data, then measure backgrounds with remaining 2/3 sample.
- Verify background estimates by loosening cuts and comparing observed and predicted rates.
- Use MC to measure geometrical acceptance for $K^+ \to \pi^+ \nu\bar{\nu}$. Verify by measuring $\mathcal{B}(K^+ \to \pi^+\pi^0)$.

Example: $K^+ \to \pi^+\pi^0$ background rejection





Left: Kinematically select $K^+ \to \pi^+\pi^0$ and apply the photon veto. Photon veto: Typically 2-5 ns time windows and 0.2 - 3 MeV energy thresholds

Right: Select photons. Phase space cuts in P, R, E.

E787 and E949 analysis strategy

- "Blind" analysis. Don't examine signal region until all backgrounds verified.
- A priori identification of background sources.
- Suppress each background source with at least two independent cuts.
- Backgrounds cannot be reliably simulated: measure with data by inverting cuts and measuring rejection taking any (small) correlations into account.
- To avoid bias, set cuts using 1/3 of data, then measure backgrounds with remaining 2/3 sample.
- Verify background estimates by loosening cuts and comparing observed and predicted rates.
- Use MC to measure geometrical acceptance for $K^+ \to \pi^+ \nu \bar{\nu}$. Verify by measuring $\mathcal{B}(K^+ \to \pi^+ \pi^0)$.

Verify background by loosening cuts

Define rejection $\equiv 1$ when cuts are set to produce pre-determined signal region ("signal box")

Relax cut to reduce rejection by $\times 10$. New, larger region should have $10\times$ background of signal box.

Example: For $K^+ \rightarrow \pi^+\pi^0$ background, simultaneously loosen photon veto (PV) and kinematic (KIN) cuts each by $\times 10$. Expect $10 \times 10 = 100$ times more background than that of the signal box.

Compare background prediction with observation near signal region

	PV×KIN	10×10	20×20	20×50	50×50	50×100
$K_{\pi 2}$	Observed	3	4	9	22	53
	Predicted	1.1	4.9	12.4	31.1	62.4
	TD×KIN	10×10	20×20	50×50	80×50	120×50
$K_{\mu 2}$	Observed	0	1	12	16	25
	Predicted	0.35	1.4	9.1	14.5	21.8
	TD×KIN	10×10	20×20	50×20	80×20	80×40
$K_{\mu m}$	Observed	1	1	4	5	11
	Predicted	0.31	1.3	3.2	5.2	10.4

$K_{\pi 2} \equiv K^+ \to \pi^+\pi^0$; $K_{\mu 2} \equiv K^+ \to \mu^+\nu$;

$K_{\mu m} \equiv K^+ \to \mu^+\nu\gamma$, $K^+ \to \pi^0\mu^+\nu$ and $K^+ \to \pi^+\pi^0$ with $\pi^+ \to \mu^+\nu$ decay in flight

TD$\equiv \pi \to \mu \to e$ identification, PV$\equiv$Photon Veto rej., KIN$\equiv$ kinematic rej.
$M \times N \equiv$ reduction in rejection with respect to signal region

Compare background prediction with observation near signal region

Quantify consistency: Fit $N_{\rm obs} = cN_{\rm pred}$ and expect $c = 1$.

Background	c	χ^2 Probability	Total background
$\mathrm{K}_{\pi 2}$	$0.85^{+0.12}_{-0.11}$	0.17	0.216 ± 0.023
$\mathrm{K}_{\mu 2}$	$1.15^{+0.25}_{-0.21}$	0.67	0.044 ± 0.005
$\mathrm{K}_{\mu m}$	$1.06^{+0.35}_{-0.29}$	0.40	0.024 ± 0.010

Deviation of c from unity is taken into account in evaluation of $\mathcal{B}(\mathrm{K}^+ \to \pi^+ \nu\bar{\nu})$

Beam and CEX background is 0.014 ± 0.003

The calculated number of background events in the signal region is 0.30 ± 0.03 from all background sources.

E787 and E949 analysis strategy

- "Blind" analysis. Don't examine signal region until all backgrounds verified.
- A priori identification of background sources.
- Suppress each background source with at least two independent cuts.
- Backgrounds cannot be reliably simulated: measure with data by inverting cuts and measuring rejection taking any (small) correlations into account.
- To avoid bias, set cuts using 1/3 of data, then measure backgrounds with remaining 2/3 sample.
- Verify background estimates by loosening cuts and comparing observed and predicted rates.
- Use MC to measure geometrical acceptance for $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$. Verify by measuring $\mathcal{B}(\mathrm{K}^+ \to \pi^+\pi^0) = 0.215 \pm 0.005$.
  World average value is 0.2113 ± 0.0014.

E949 improved analysis strategy[†]

1. E787 background estimation methods are reliable
2. Divide signal region into cells and calculate background (b_i) and signal acceptance (s_i) for each cell. Example: Tighten PV cut to select subregion with 1/10 of the total predicted $K^+ \to \pi^+\pi^0$ background within "signal box"
3. Can calculate $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ using s_i/b_i of any cells containing candidates using likelihood ratio method.
4. Increase total size of signal region to increase acceptance at cost of more total background

[†] With age comes wisdom.

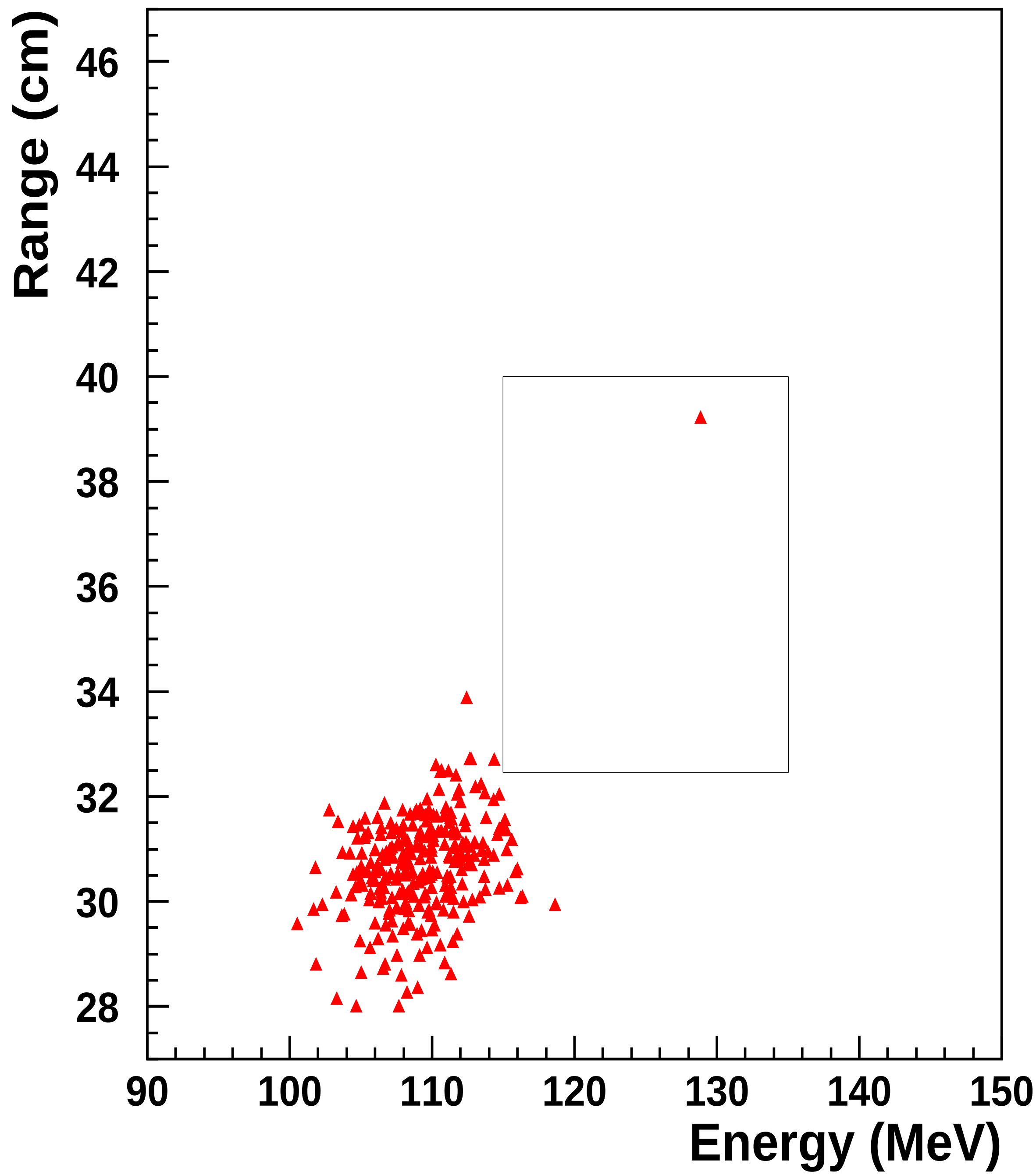
Opening the box

Range (cm) *vs* Energy (MeV) for E949 data after all other cuts applied.

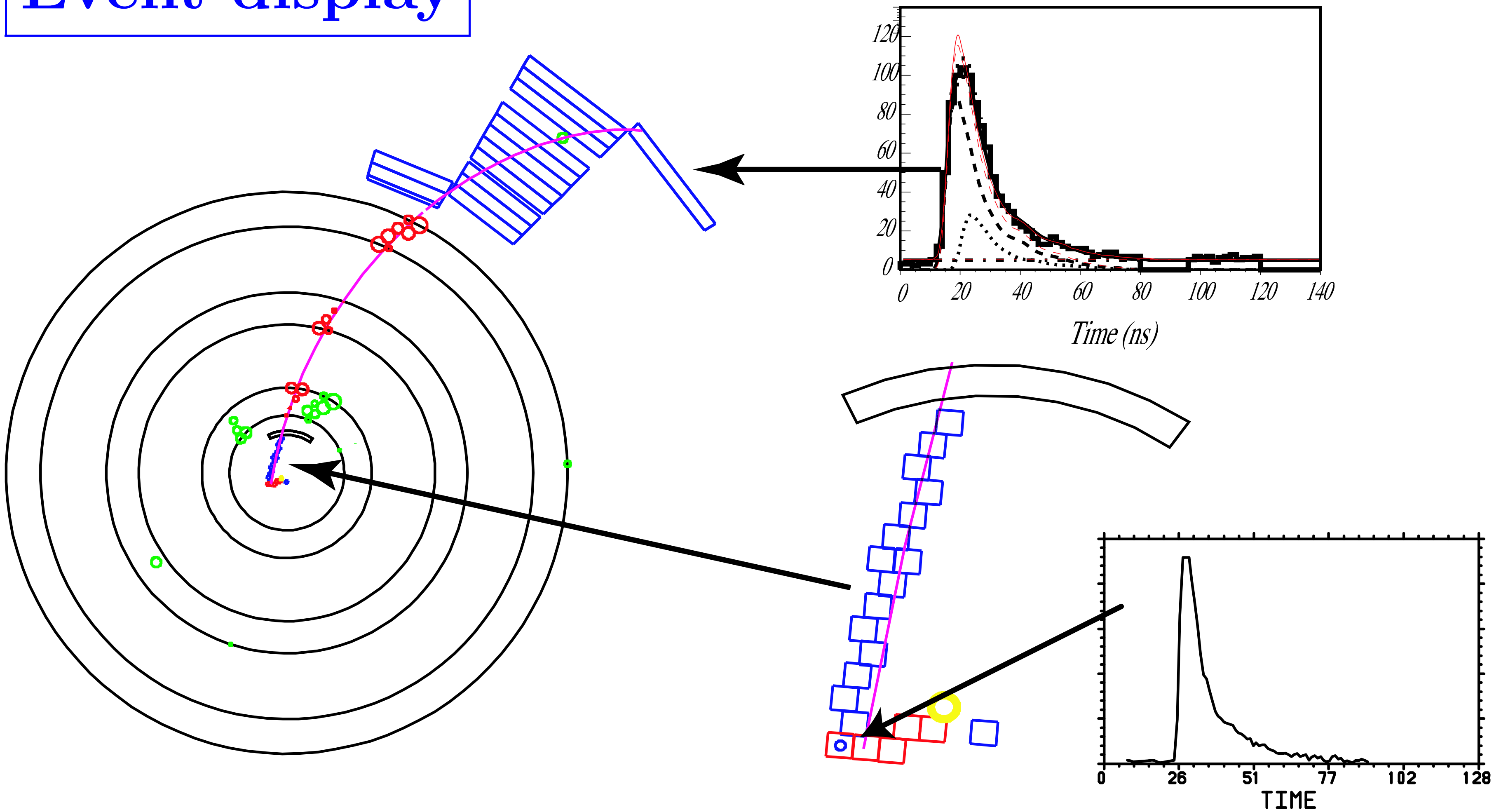
Solid line shows signal region.

Single candidate found.

Cluster near 110 MeV is unvetoed $K^+ \to \pi^+\pi^0$.



Event display



How likely is it that the candidate is due to known background?

Question: Suppose we do 100 experiments, how many will have a candidate from a known background source that is as signal-like or more signal-like than the observed candidate?

Answer: ~ 7

The sum of background in all cells with s_i/b_i greater or equal to the cell containing the observed candidate is 0.077. The probability that 0.077 could produce one or more events is 0.074 ($\sim 7/100$).

The E949 candidate is more likely to be due to background than the two E787 candidates.

Candidate	E787A	E787C	E949A
Probability	0.006	0.02	0.07

	E787		E949
Stopped K$^+$ (N_K)	5.9×10^{12}		1.8×10^{12}
Total Acceptance	0.0020 ± 0.0002		0.0022 ± 0.0002
Total Background	0.14 ± 0.05		0.30 ± 0.03
Candidate	E787A	E787C	E949A
S_i/b_i	50	7	0.9
W_i	0.98	0.88	0.48

b_i = background of cell containing candidate

$S_i \equiv \mathcal{B} A_i N_K$ = signal for cell containing candidate

$A_i \equiv$ acceptance

$\mathcal{B}$ = measured central value of $K^+ \to \pi^+ \nu\bar{\nu}$ branching fraction

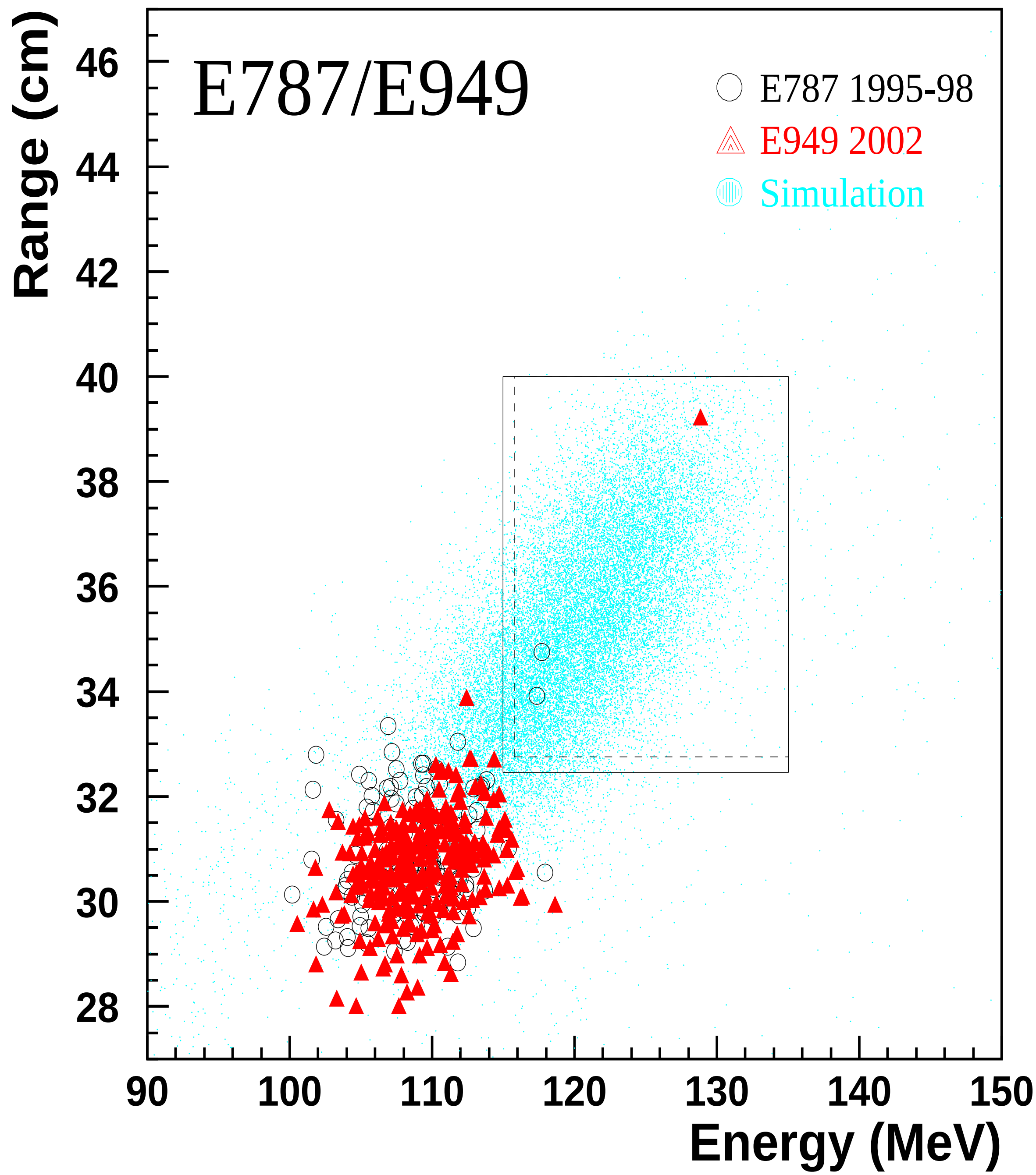
$W_i \equiv S_i/(S_i + b_i)$ = event weight

Event weight W_i and S_i/b_i assumes SM signal hypothesis as well as calculated background.

Range (cm) *vs* Energy (MeV) for combined E787 and E949 data after all other cuts applied.

Dashed line is E787 signal region.

Solid line is E949 signal region.



Combined E787 and E949 results for $\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu})$

$\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\overline{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10}$ (68%CL interval)

$\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\overline{\nu}) > 0.42 \times 10^{-10}$ at 90%CL.

SM prediction†: $\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu}) = (0.77 \pm 0.11) \times 10^{-10}$

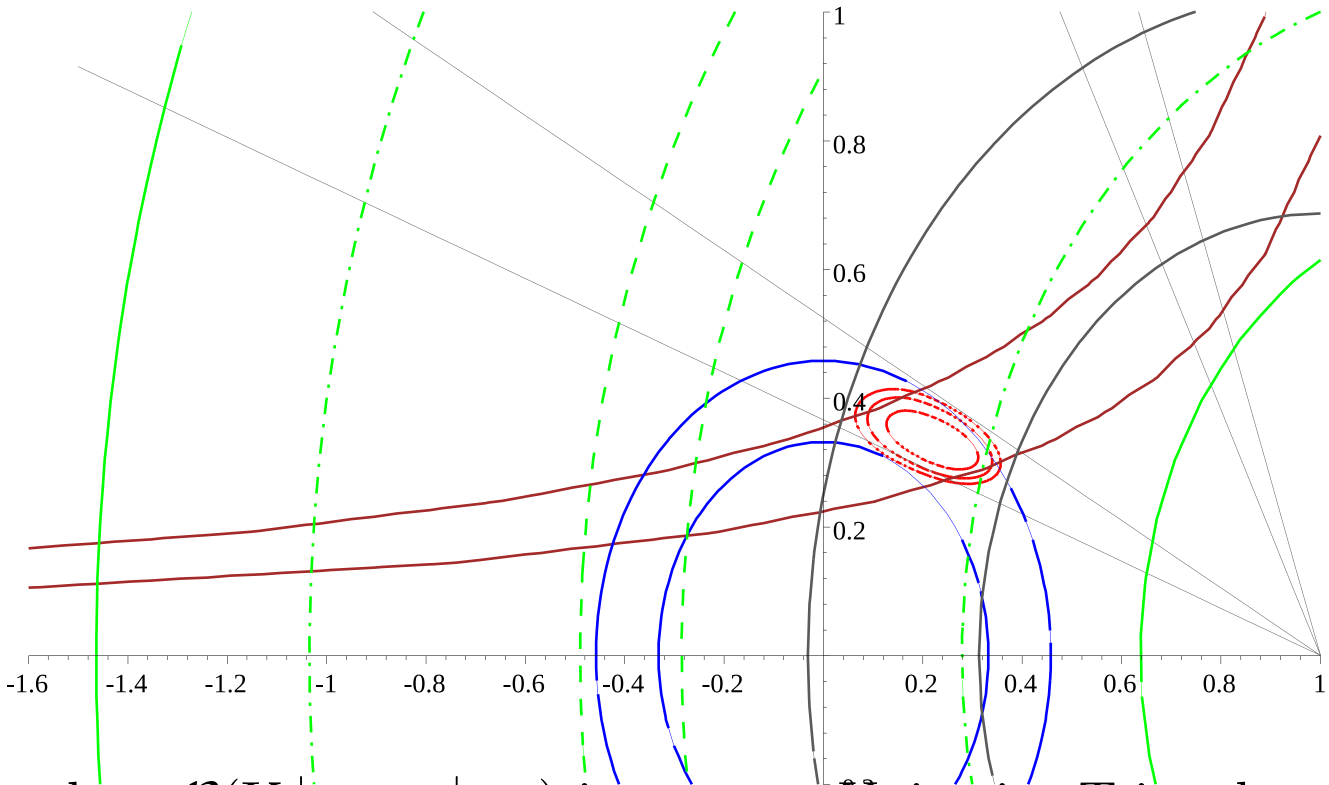
The probability that background alone gave rise to the three observed events or to any more signal-like configuration is 0.001.

E787 result: $\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\overline{\nu}) = (1.57^{+1.75}_{-0.82}) \times 10^{-10}$

Combined results: PRL **93**(2004) 31801, hep-ex/0403036

† Reference: Buchalla& Buras, NP**B548** 309 (1999);
Isidori, hep-ph/0307014;Buras, hep-ph/0402112

Impact of $\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu})$ on Unitarity Triangle

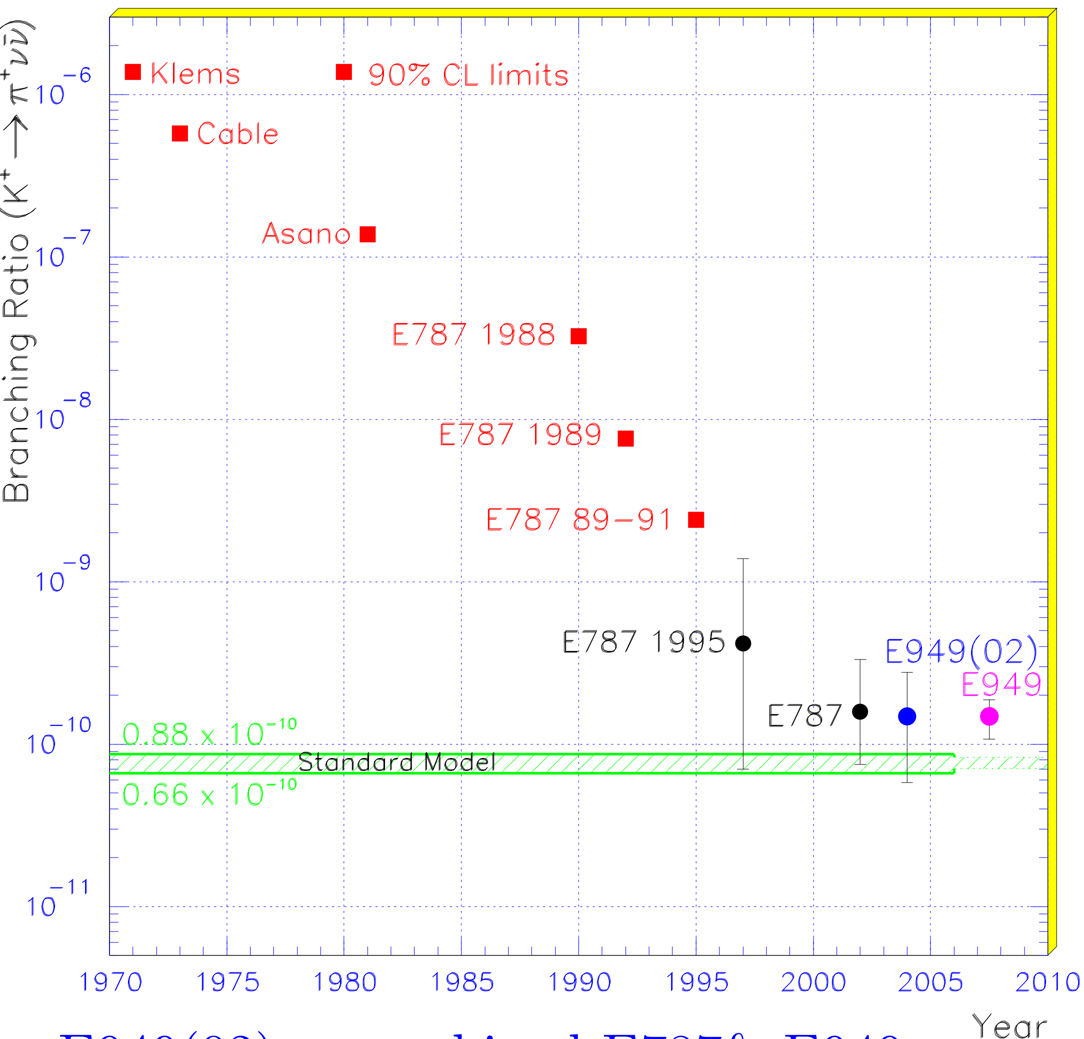


Green lines show $\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu})$ impact on Unitarity Triangle: central value (dashed), 68% interval (dot-dash), 90% interval (solid). Theoretical uncertainty is included.

Red ovals show 68%, 90% and 95% areas from other measurements ($|V_{ub}|$, ϵ_K, $\sin 2\beta$, Δm_d, $\Delta m_s/\Delta m_d$)

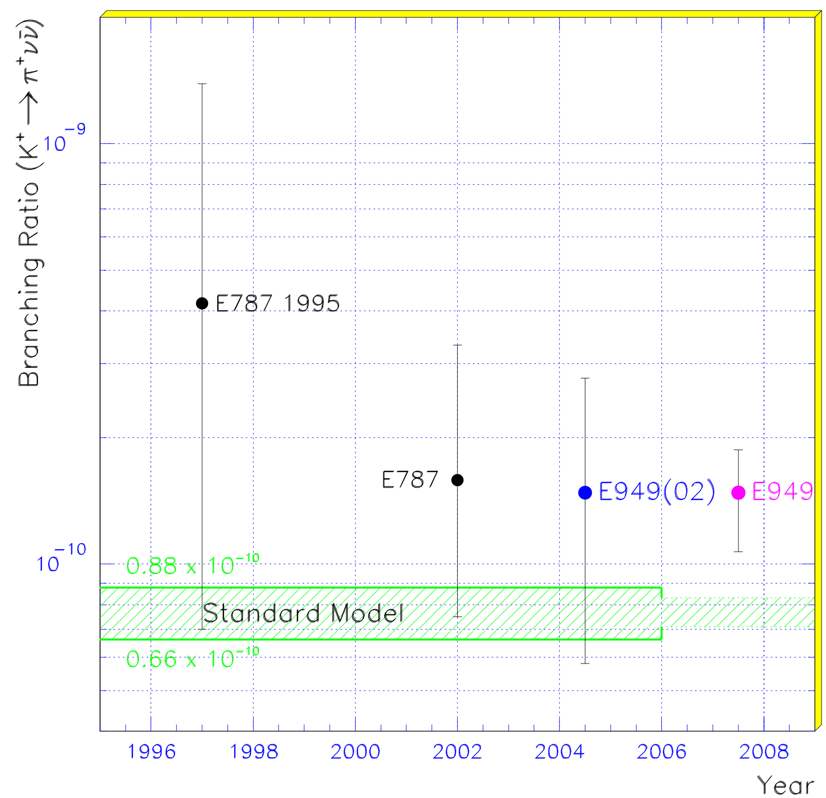
Provided by Gino Isidori.

Progress in $K^+ \to \pi^+ \nu \bar{\nu}$



$E949(02)$ = combined E787& E949.

E949 projection with full running period.



Narrowing of "SM prediction" assumes measurement of B_s mixing consistent with prediction.

$K_L^0 \to \pi^0 \nu\bar{\nu}$: Fifteen years ago

PHYSICAL REVIEW D VOLUME 39, NUMBER 11 1 JUNE 1989

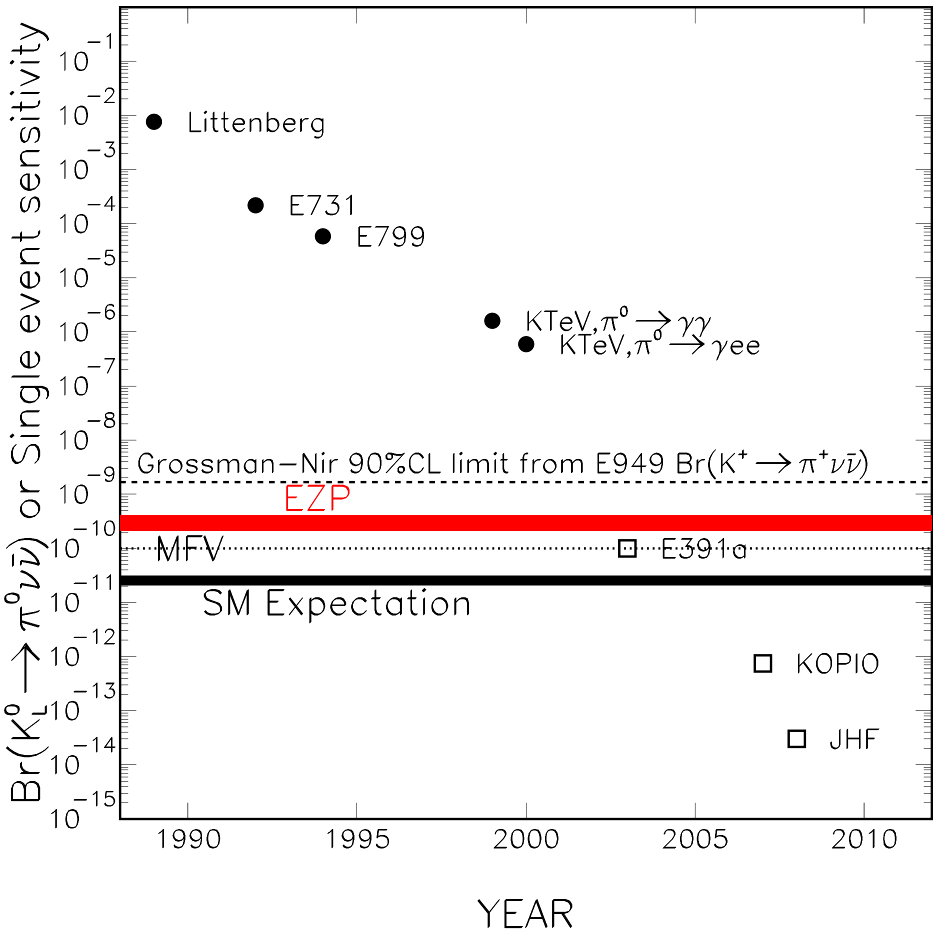
CP-violating decay $K_L^0 \to \pi^0 \nu\bar{\nu}$

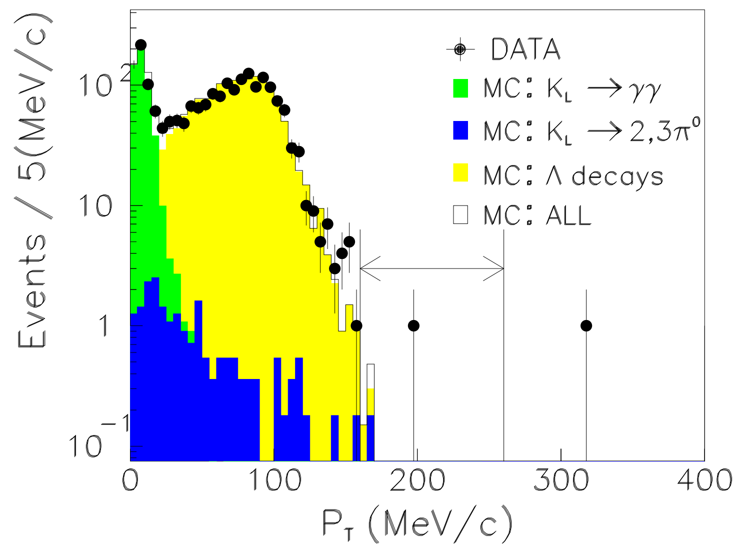
Laurence S. Littenberg
Department of Physics, Brookhaven National Laboratory, Upton, New York 11973
(Received 6 January 1989)

The process $K_L^0 \to \pi^0 \nu\bar{\nu}$ offers perhaps the clearest window yet proposed into the origin of CP violation. The largest expected contribution to this decay is a direct CP-violating term at $\approx$few$\times 10^{-12}$. The indirect CP-violating contribution is some *3 orders of magnitude* smaller, and CP-conserving contributions are also estimated to be extremely small. Although this decay has never been directly probed, a branching ratio upper limit of $\sim 1\%$ can be extracted from previous data on $K_L^0 \to 2\pi^0$. This leaves an enormous range in which to search for new physics. If the Kobayashi-Maskawa (KM) model prediction can be reached, a theoretically clean determination of the KM product $\sin\theta_2 \sin\theta_3 \sin\delta$ can be made.

"Experimentally, the problems are perhaps best represented by the statement that nobody has yet shown that a measurement of this decay is absolutely impossible." F.J.Gilman, "CP Violation in Rare K Decays", *Blois CP Violations* 1989:481-496

$K^0_L \to \pi^0 \nu\bar{\nu}$ Progress



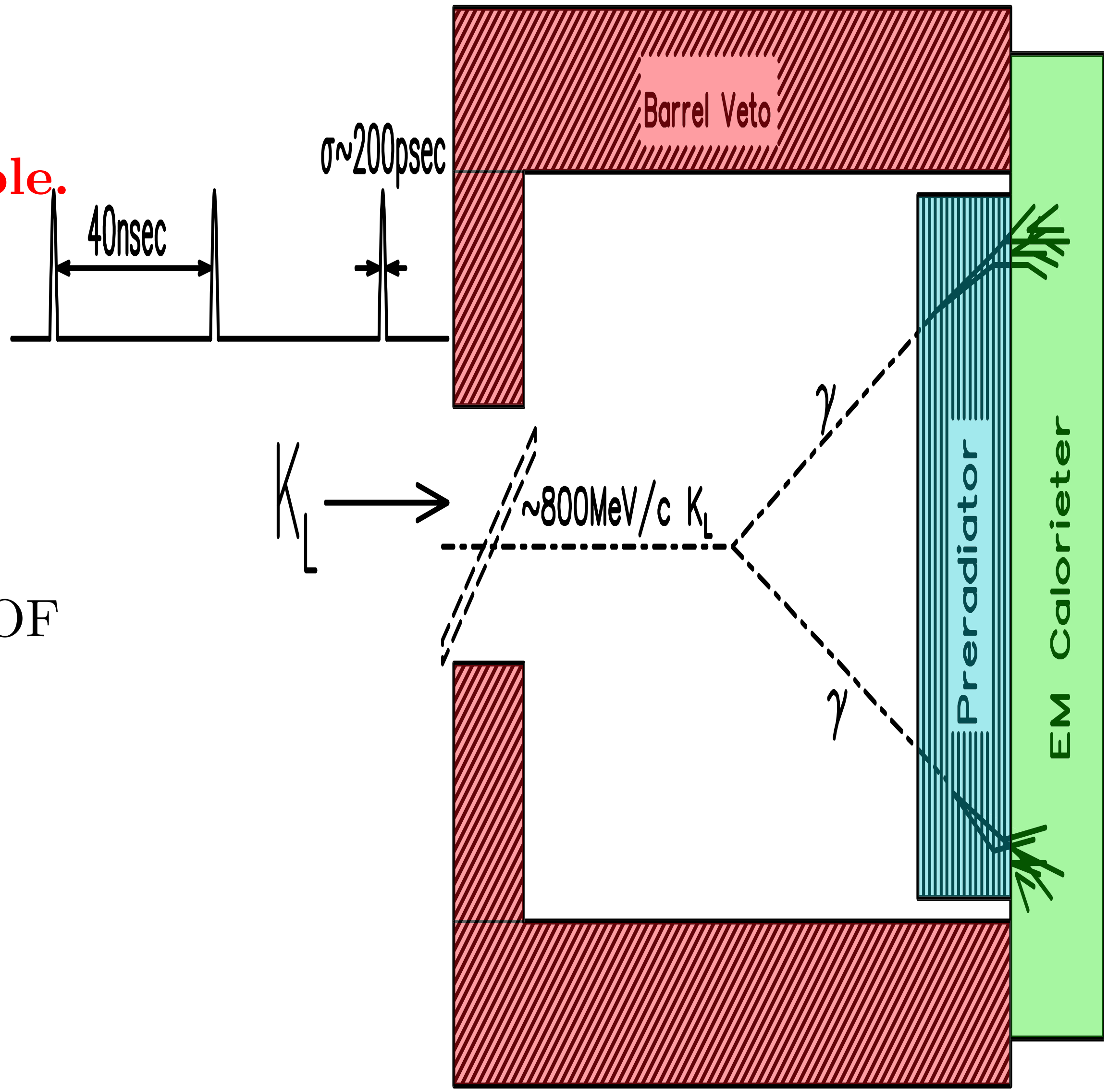


KTeV result with "pencil" K^0_L beam (PL**B447** (1999) 240). E391a, JHF expts use a similar technique.

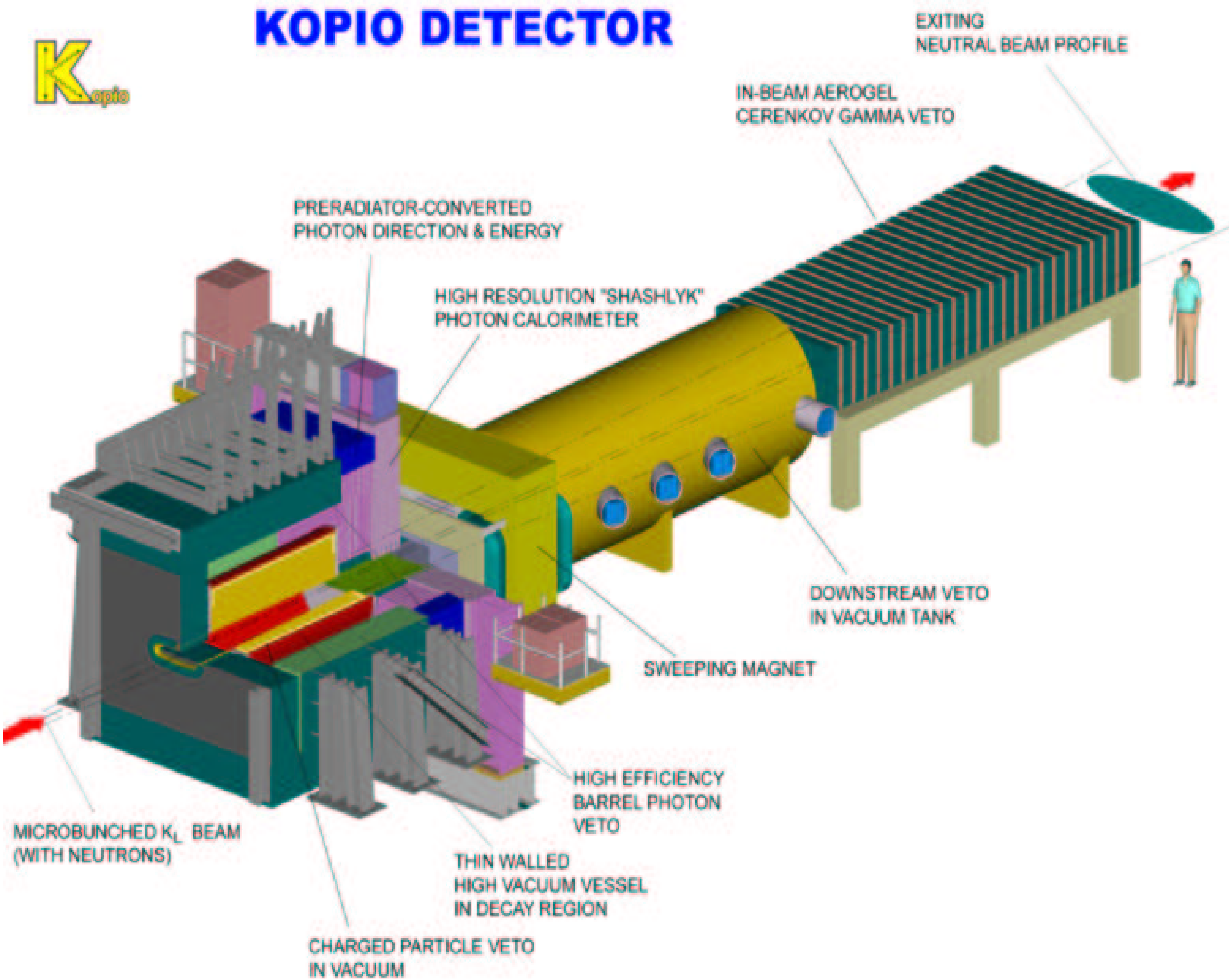
The KOPIO Technique: Work in K_L^0 CMS

Measure everything possible.

- Microbunched K_L^0 beam
- Measure γ directions in PR
- Measure γ energy in CAL
- Reconstruct π^0 from $\gamma\gamma$
- Measure K_L^0 velocity from TOF
- Photon veto
- Charged track veto
- Kinematic veto



D

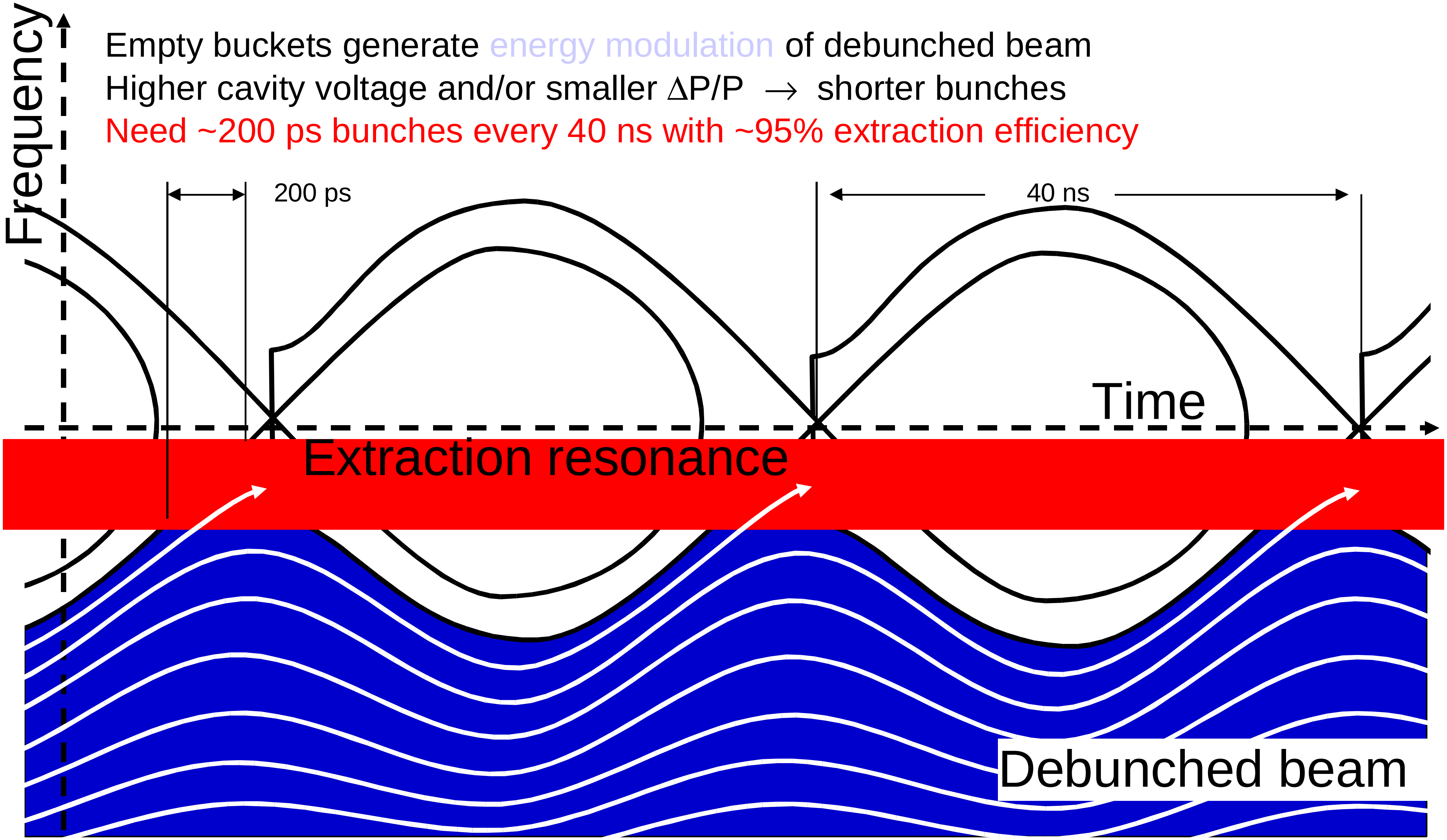

KOPIO DETECTOR
EXITING
NEUTRAL BEAM PROFILE
IN-BEAM AEROGEL
CERENKOV GAMMA VETO
PRERADIATOR-CONVERTED
PHOTON DIRECTION & ENERGY
HIGH RESOLUTION "SHASHLYK"
PHOTON CALORIMETER
DOWNSTREAM VETO
IN VACUUM TANK
SWEEPING MAGNET
HIGH EFFICIENCY
BARREL PHOTON
VETO
MICROBUNCHED K_L BEAM
(WITH NEUTRONS)
THIN WALLED
HIGH VACUUM VESSEL
IN DECAY REGION
CHARGED PARTICLE VETO
IN VACUUM

Micro-bunched slow extraction

Empty buckets generate energy modulation of debunched beam

Higher cavity voltage and/or smaller $\Delta P/P \rightarrow$ shorter bunches

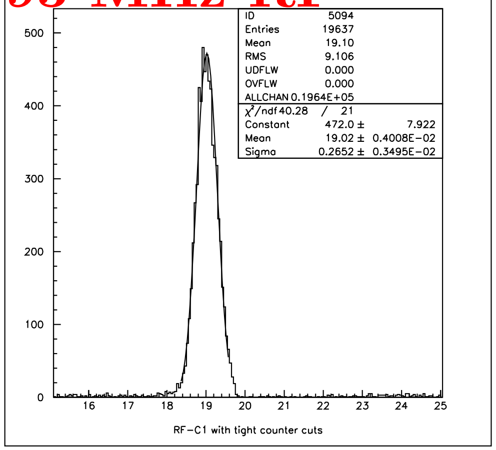
Need ~200 ps bunches every 40 ns with ~95% extraction efficiency



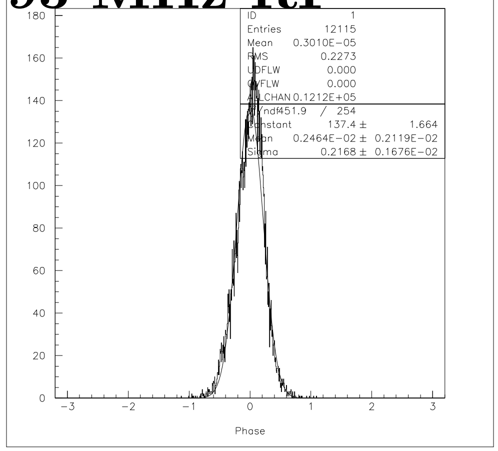
Microbunch width σ and interbunch extinction E

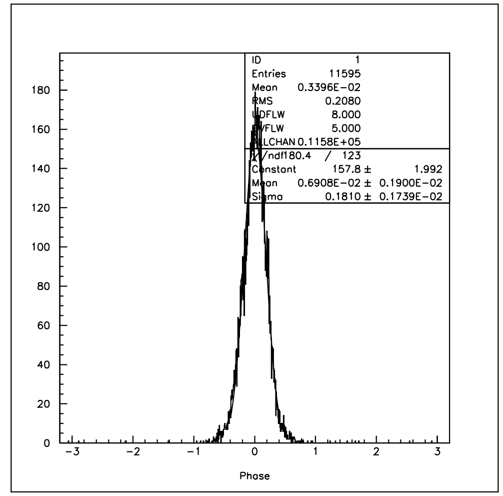
25/100 MHz RF

93 MHz RF



93 MHz RF



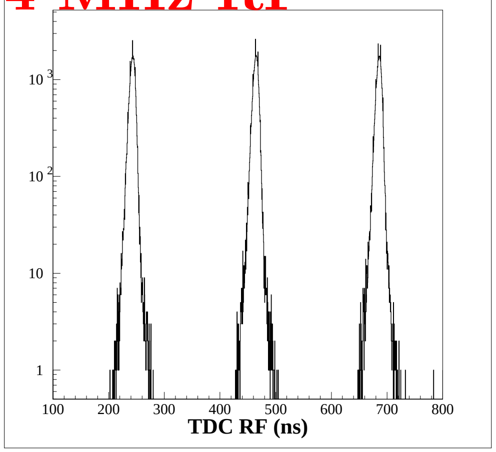


meas. $\sigma = 240$ ps

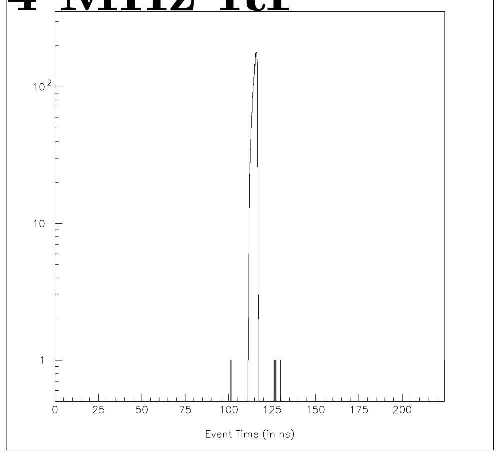
pred. $\sigma = 215$ ps

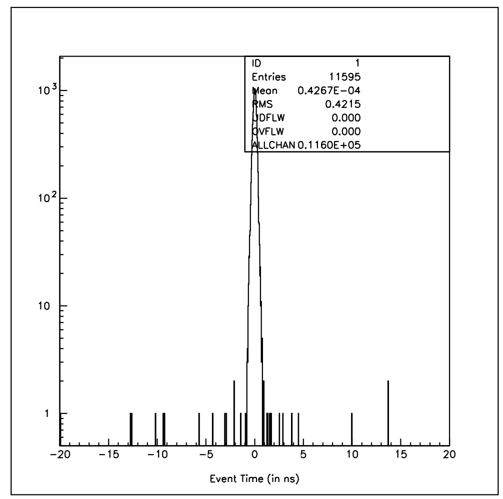
Predicted $\sigma = 185$ ps

4 MHz RF



4 MHz RF





meas. $E = (7 \pm 5) \times 10^{-6}$

pred. $E < .001$

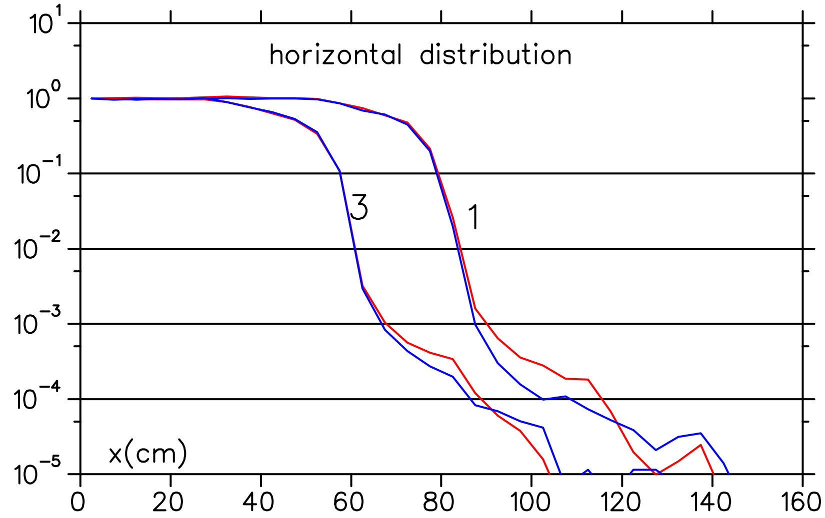
Predicted $E \sim 0.002$

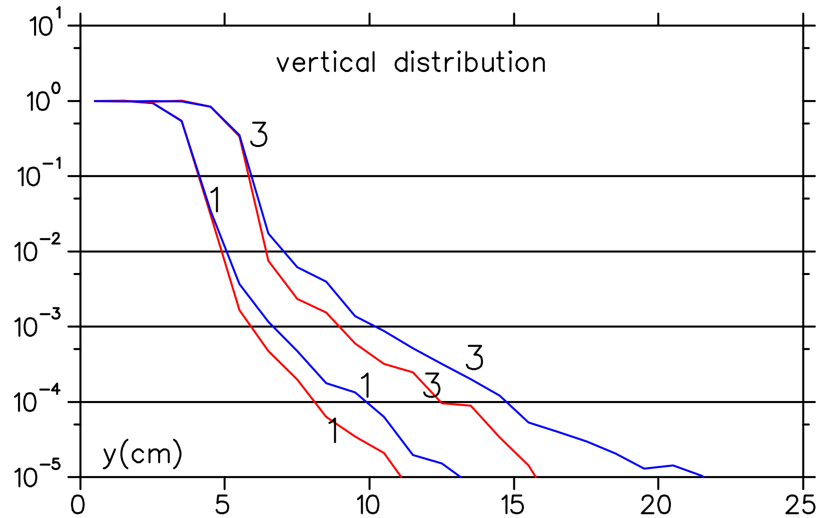
KOPIO neutral beam

The central production angle of the KOPIO neutral beam is 42.5°. The aspect ratio is 100×5 mrad^2 (horiz $\times$ vert) after passing thru 5 cm of Pb, sweeping magnets and a collimation system.

Expect ~ 3.5 K_L^0 and $\sim 600(300)$ n with $E(n) > 10(262)$ MeV per microbunch.

Figure shows the calculated normalized neutron profiles for 2 aspect ratios at the front of the pre-radiator (1400 cm from target) Aspect ratio # 1 is 100×5 mrad^2.

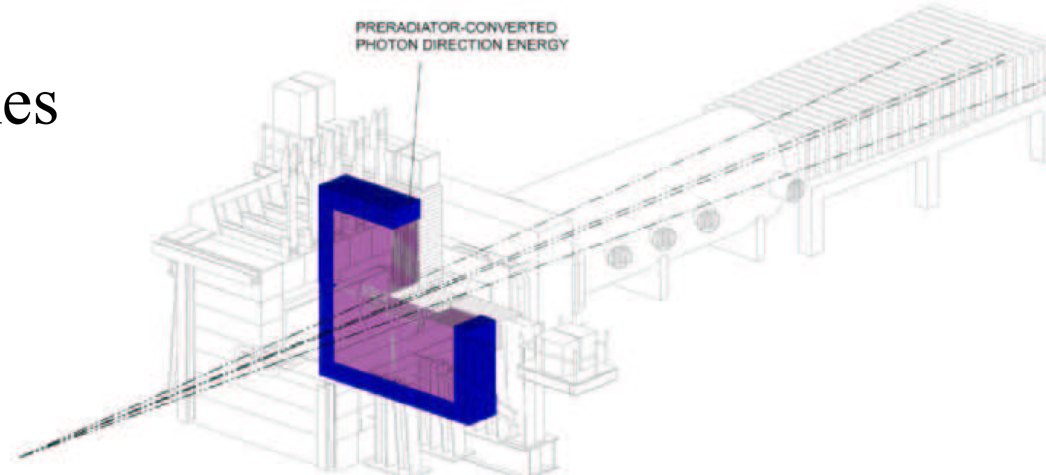


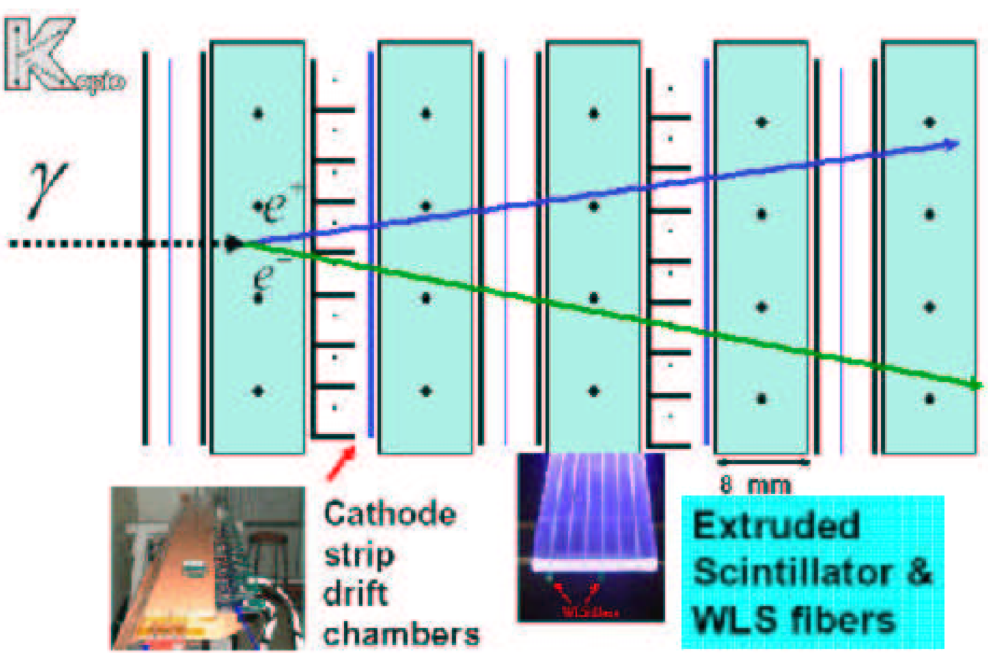


D

Preradiator

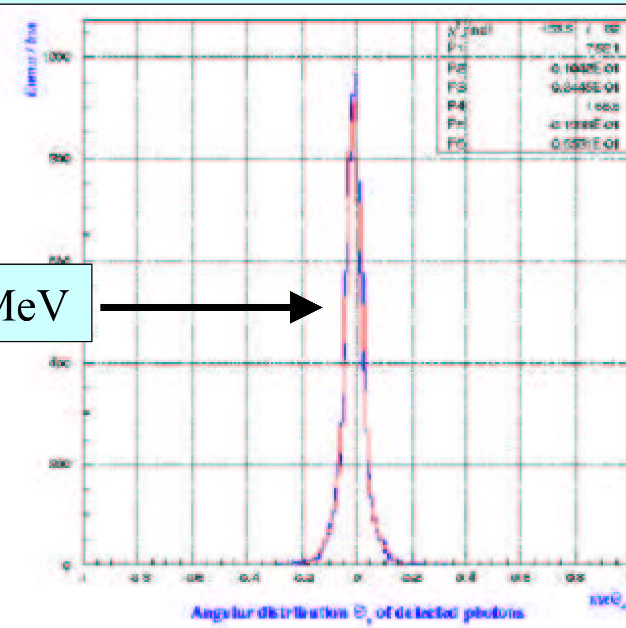
$2\ X_0$ alternating DC & scint. planes
4m × 4m (four quadrants)
200,000 channels



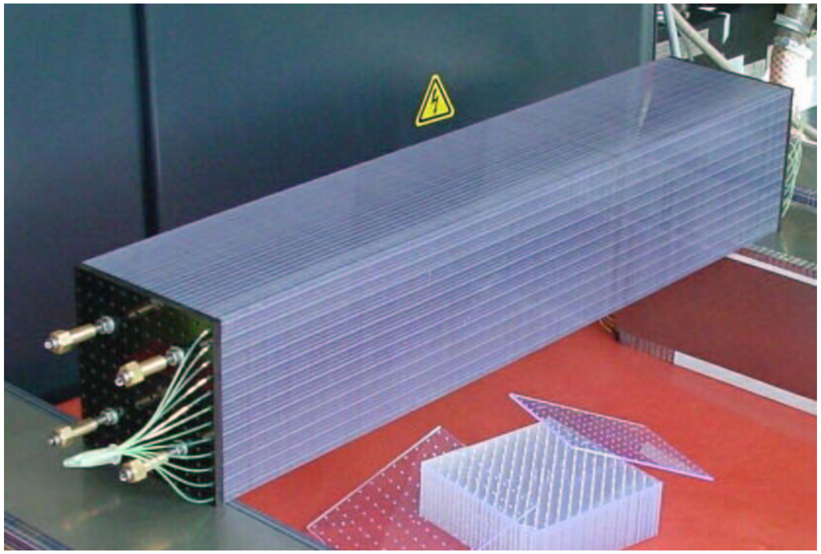


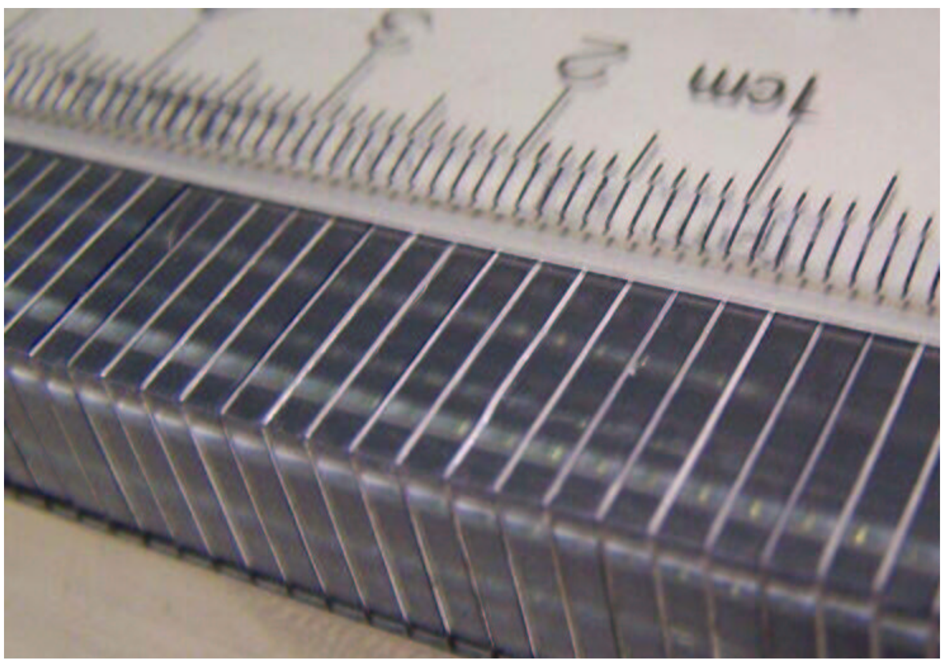
γ angular resolution measured at NSLS

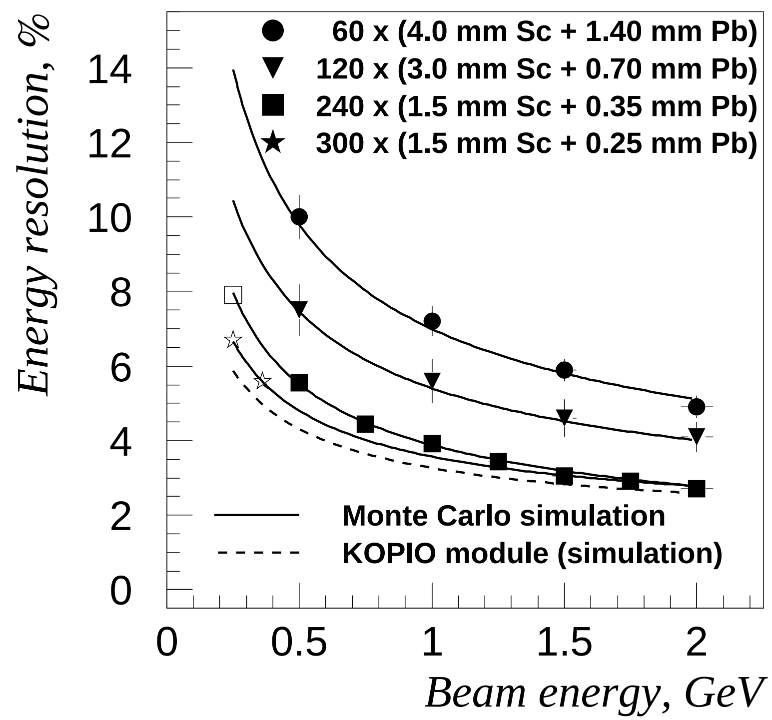
σ ~ 25 mr @ 250MeV



Shashlyk calorimeter energy resolution (physics/0310047)







- ● BNL E865
- ▼ BNL E923 prototype
- ■ KOPIO prototype
- ⋆ another KOPIO prototype

KOPIO Charged particle veto

Thin scintillator read directly by PMTs in vacuum.

Need $\bar{\epsilon}(\pi^-) < \times 10^{-4}$ and $\bar{\epsilon}(\pi^+) < 10^{-5}$.

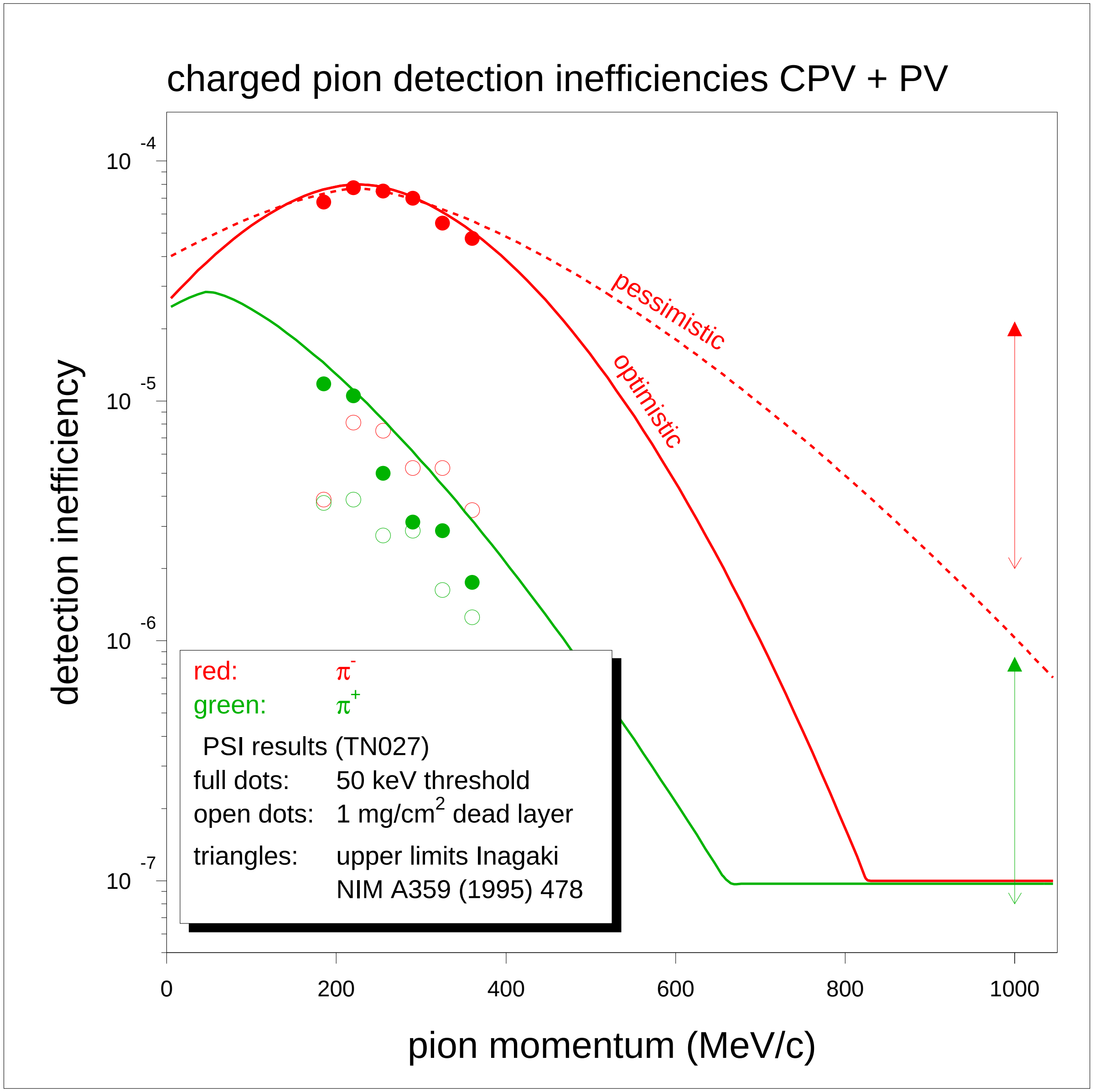
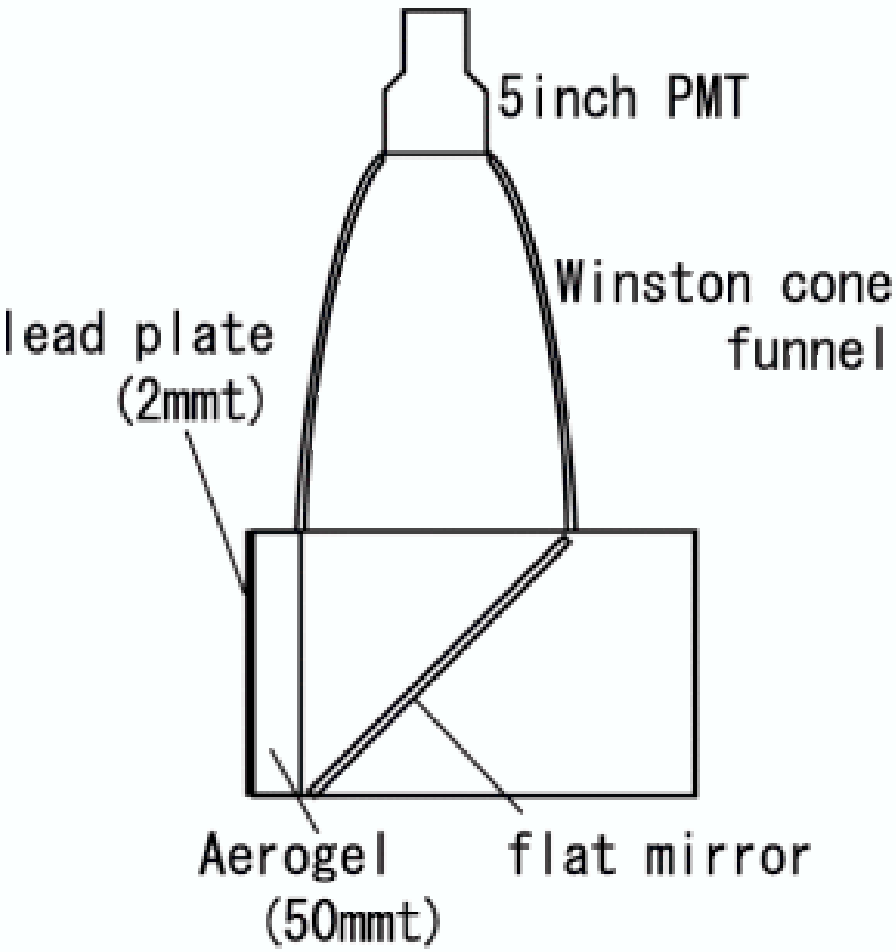
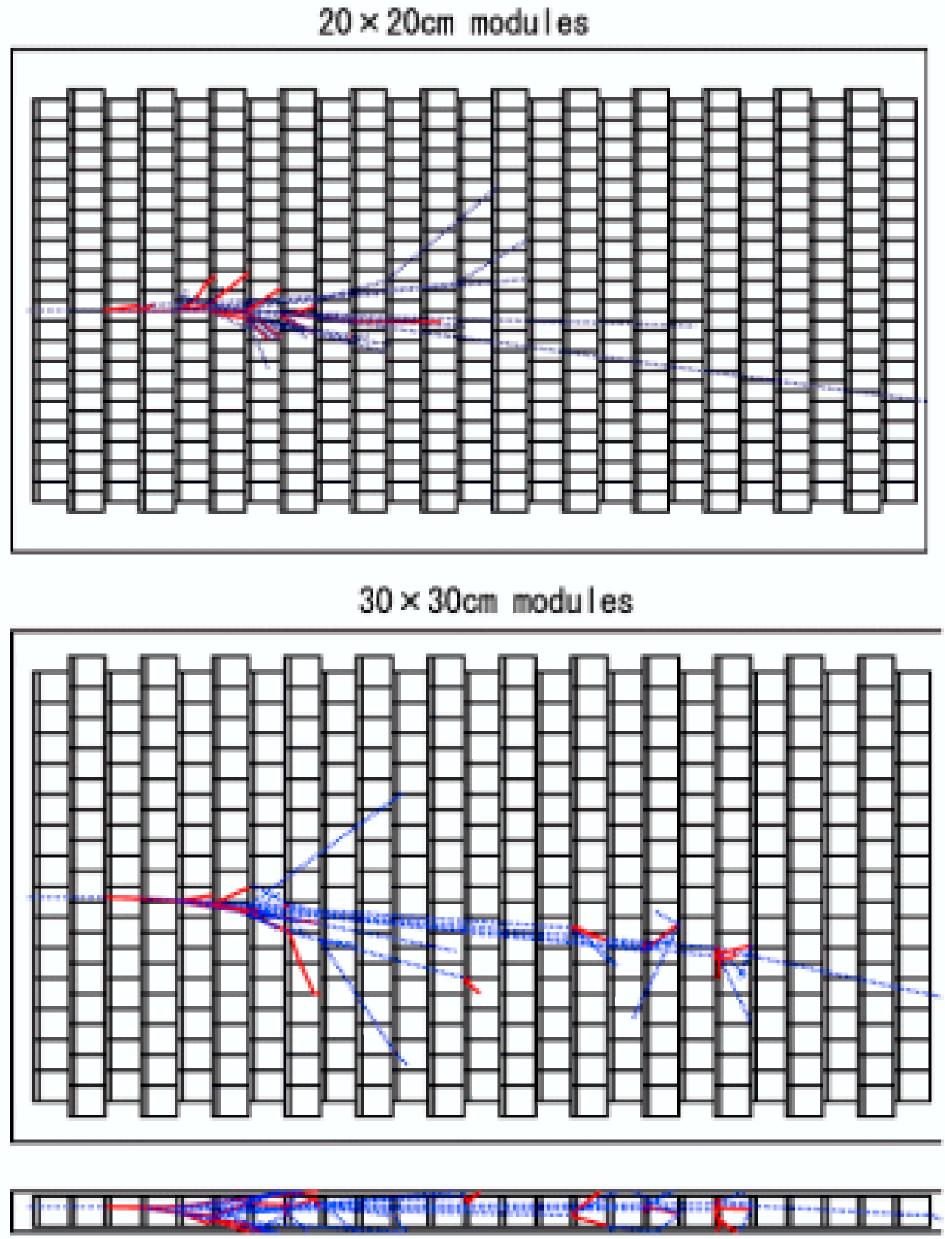


Fig.1:Base design of catcher



one module

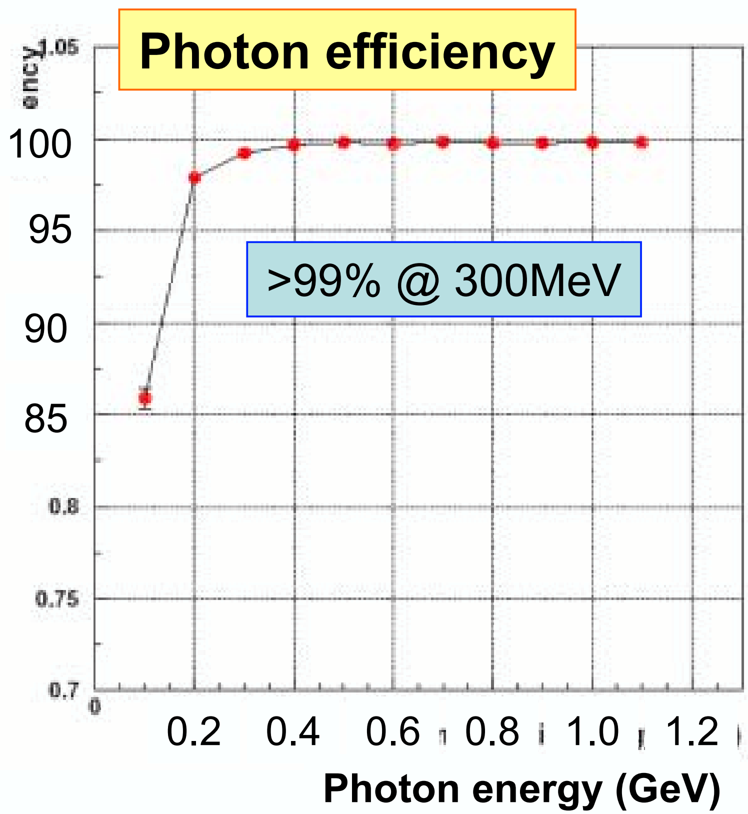


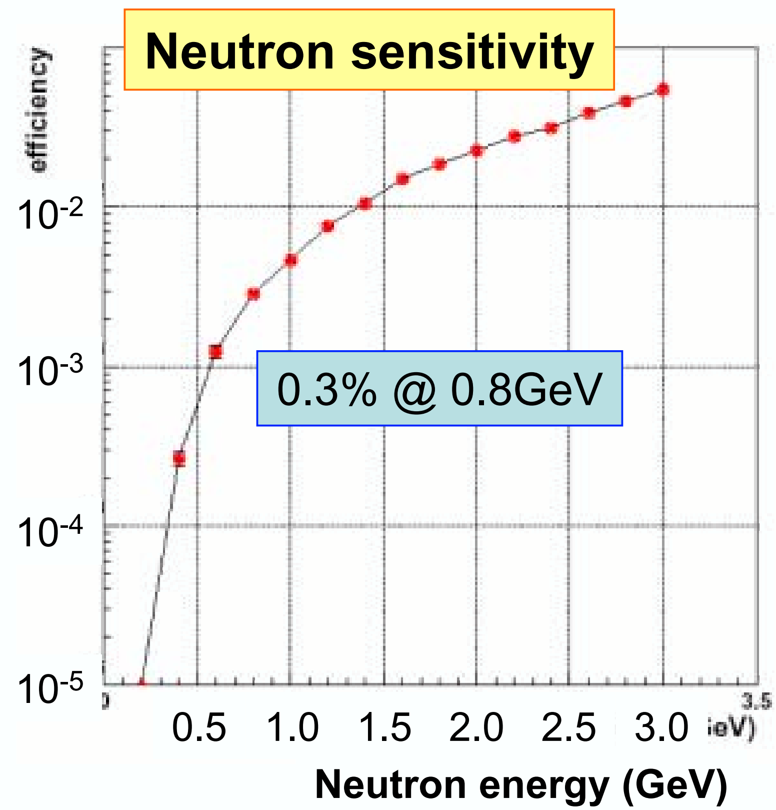
distribution

Expected performance with current design

Photon efficiency / Neutron sensitivity

» Average over +/- 10cm(y), normal incident to Catcher





Background suppression tools

K_L^0 Decay	$\mathcal{B}/3\times10^{-11}$	Kinematic	Photon veto	Charged veto
$\pi^0\pi^0$ even	3.1×10^7	E^*_π	$\surd\surd$	
$\pi^0\pi^0$ odd	3.1×10^7	$\lvert E^*_{1\gamma}-E^*_{2\gamma}\rvert$, $M_{\gamma\gamma}$	$\surd\surd$	
$\pi^\pm e^\mp\nu\gamma$	1.2×10^8	$M_{\gamma\gamma}$, χ^2	$\surd$	$\surd$
$\pi^+\pi^-\pi^0$	4.2×10^9	E^*_π, $E_{\rm MISS}$		$\surd\surd$
$\pi^0\pi^\pm e^\mp\nu$	1.7×10^6	E^*_π		$\surd\surd$
$\pi^0\pi^0\pi^0$	7.0×10^9	E^*_π	$\surd\surd\surd$	
$\pi^0\gamma\gamma$	5.6×10^4		$\surd\surd$	
$\gamma\gamma$	2.7×10^7	$M_{\gamma\gamma}$, E^*_π		

even $\equiv$ both γ from same π^0

odd $\equiv$ γ from different π^0

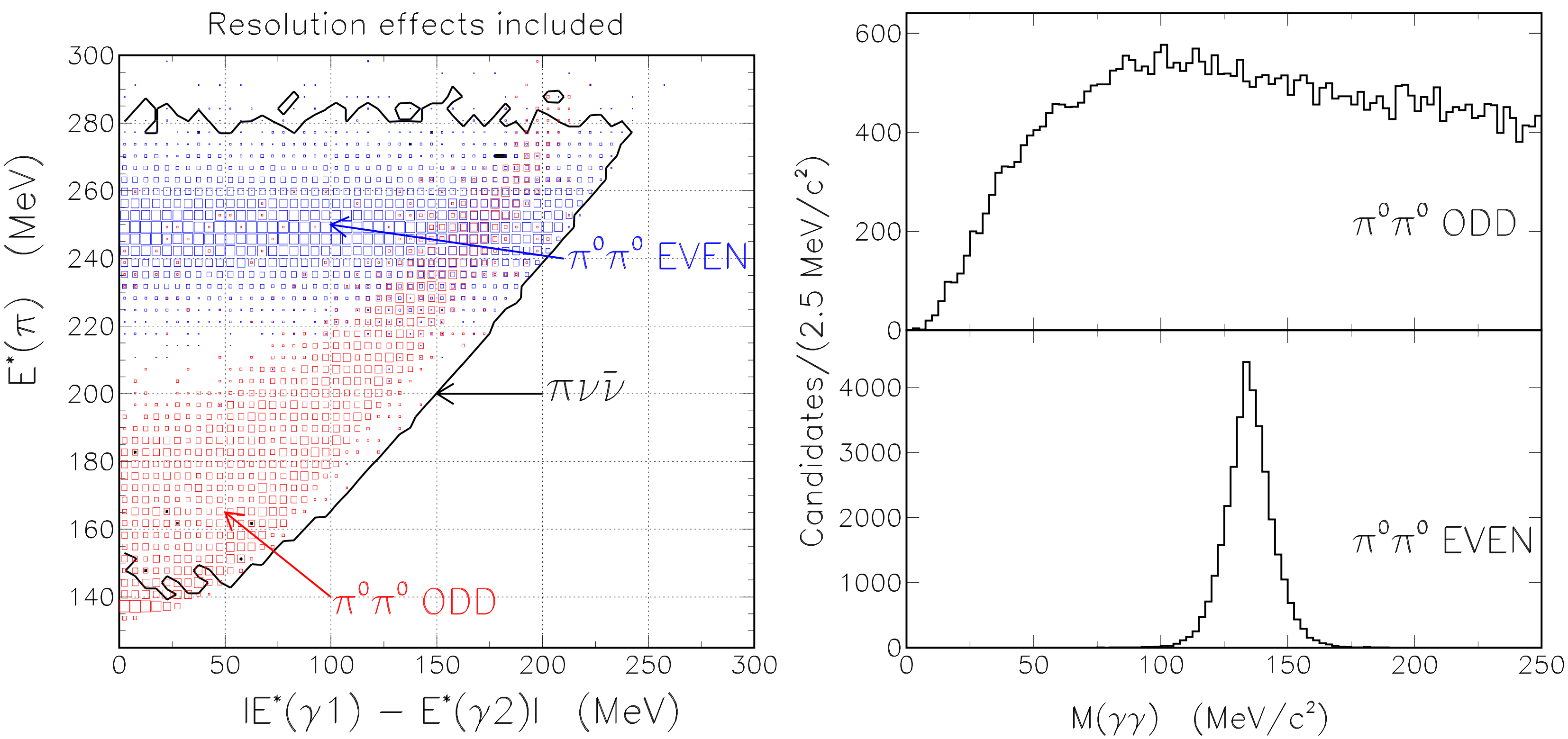
χ^2 $\equiv$ $\chi^2$of fit of γ 3-momenta to a common vertex

$M_{\gamma\gamma}$ $\equiv$ 2 photon invariant mass

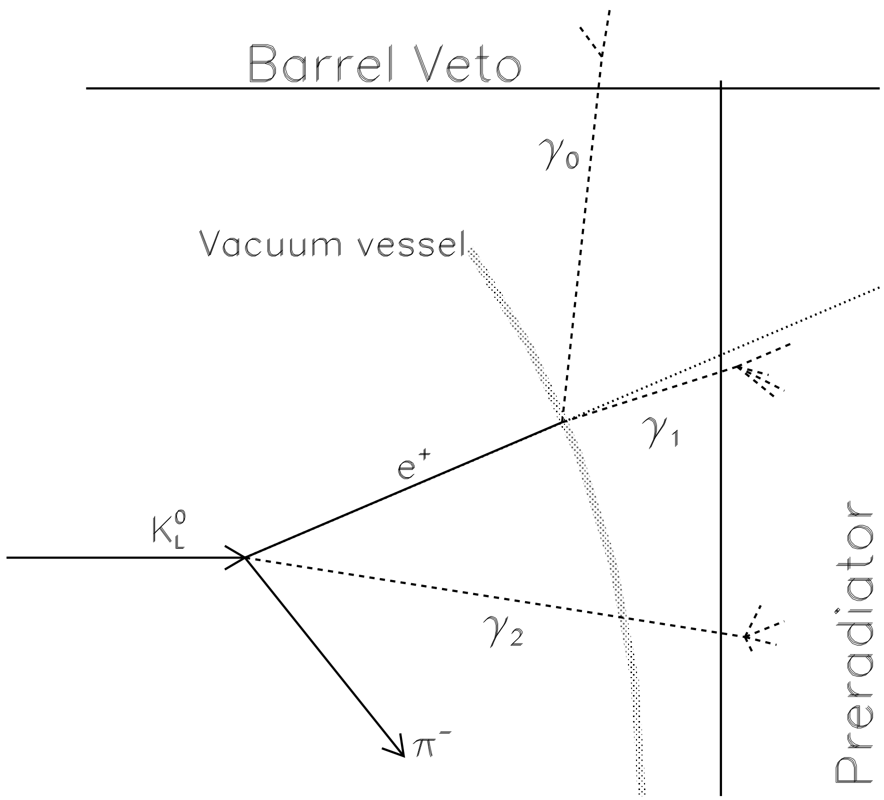
E^*_i $\equiv$ energy in K_L^0 rest frame, $i=\pi^0,\gamma_1,\gamma_2$

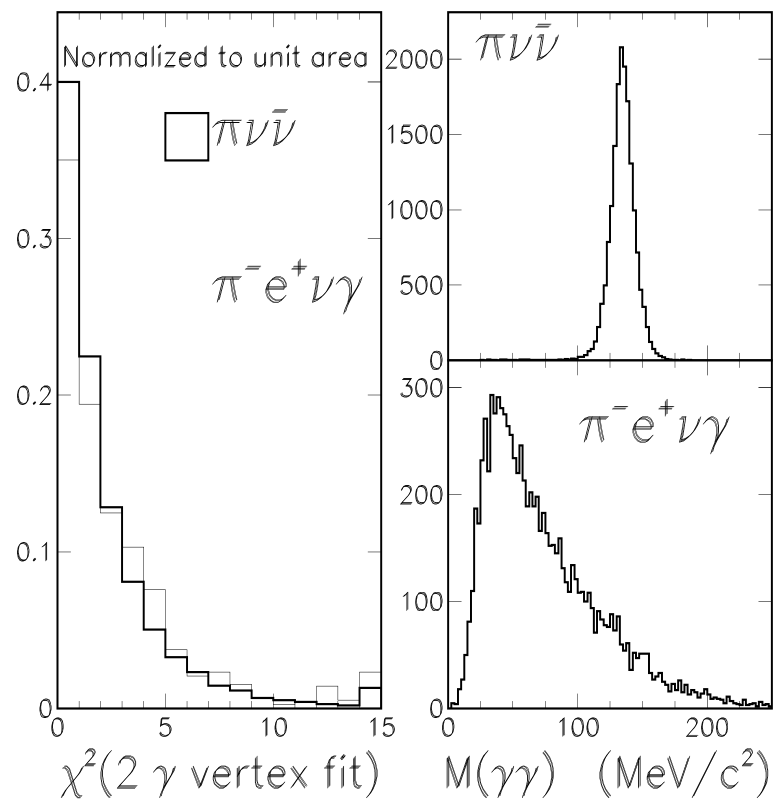
$E_{\rm MISS}$ $\equiv$ $E(K_L^0)-E(\gamma_1)-E(\gamma_2)$

Kinematic rejection of $K_L^0 \to \pi^0\pi^0$ background



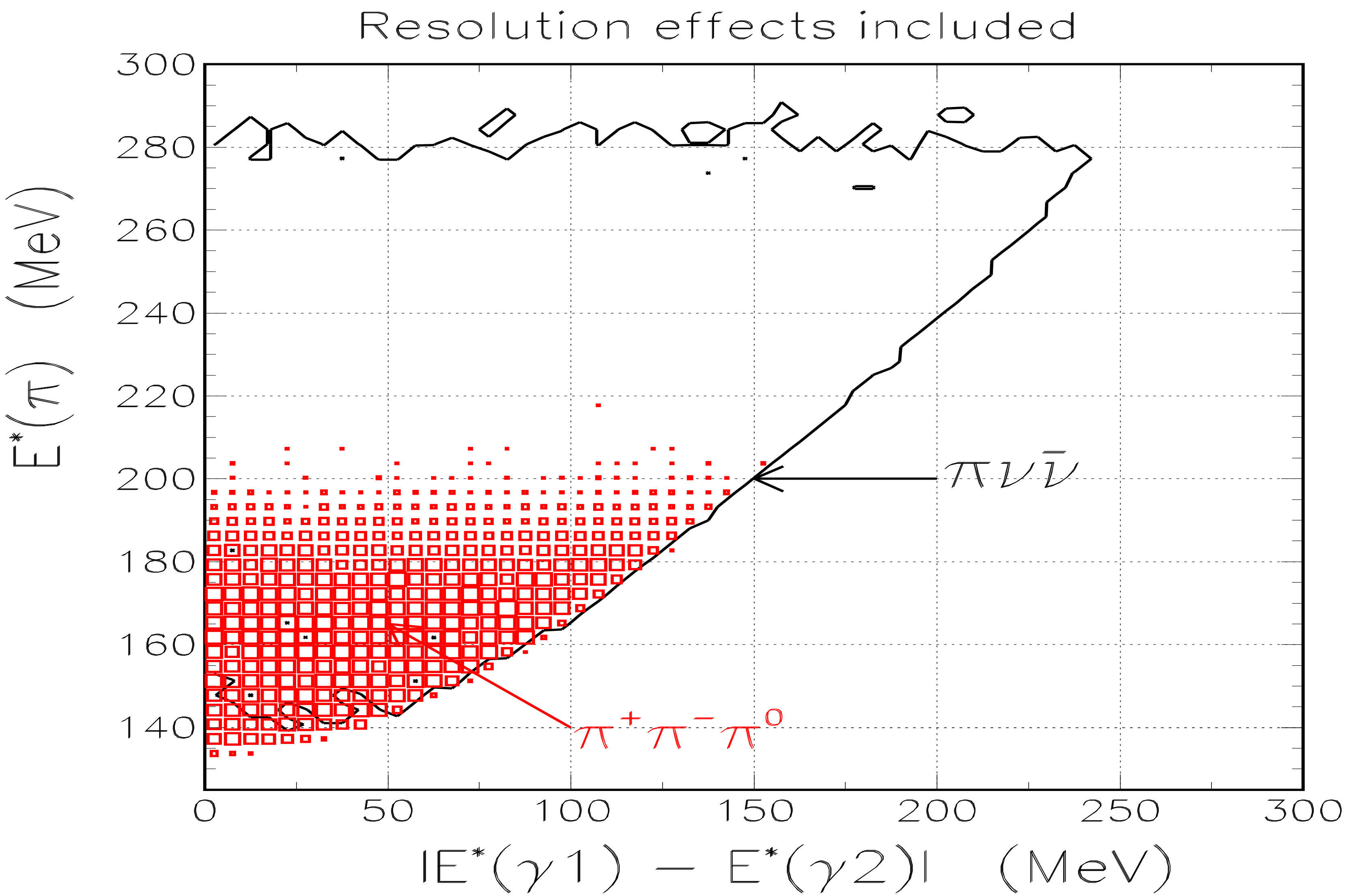
$\mathrm{K_L^0} \to \pi^- e^+ \nu \gamma_2$ $(e^+e^- \to \gamma_0\gamma_1)$ background



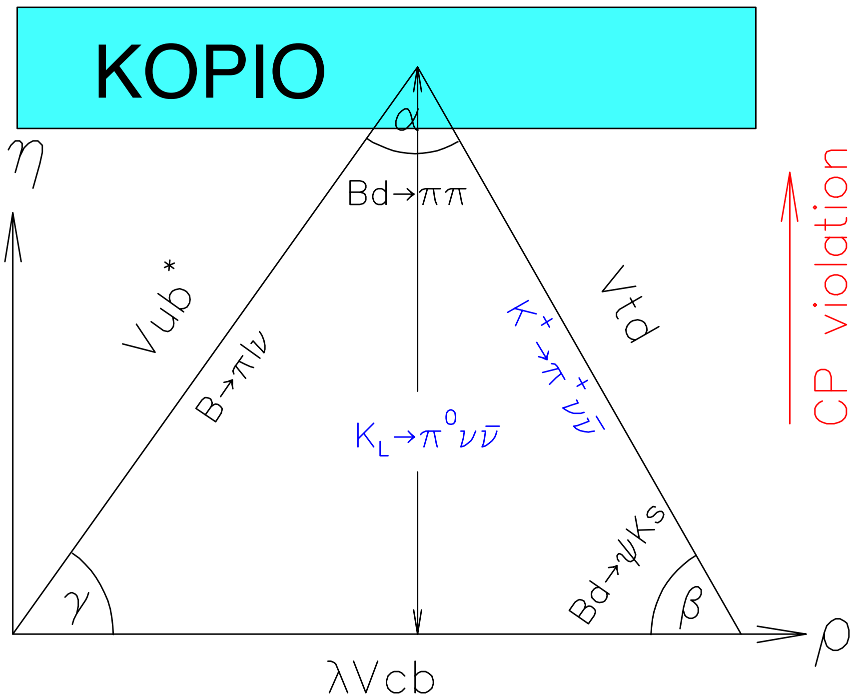


Background from $\mathrm{K_L^0} \to \pi^\pm e^\mp \nu\gamma$ occurs when the e^+ converts at the vacuum vessel. π^0 candidates are formed from $\gamma_1\gamma_2$. For $e^+e^- \to \gamma_0\gamma_1$, $p(\gamma_1) \approx p(e^+)$ and $p(\gamma_0) \approx p(e^-)$. Modest rejection possible from lower energy γ_0 and increased χ^2 from slight change of γ_1 from the original e^+ direction.

Kinematic rejection of $K^0_L \to \pi\pi\pi$ backgrounds



KOPIO signal and background estimates

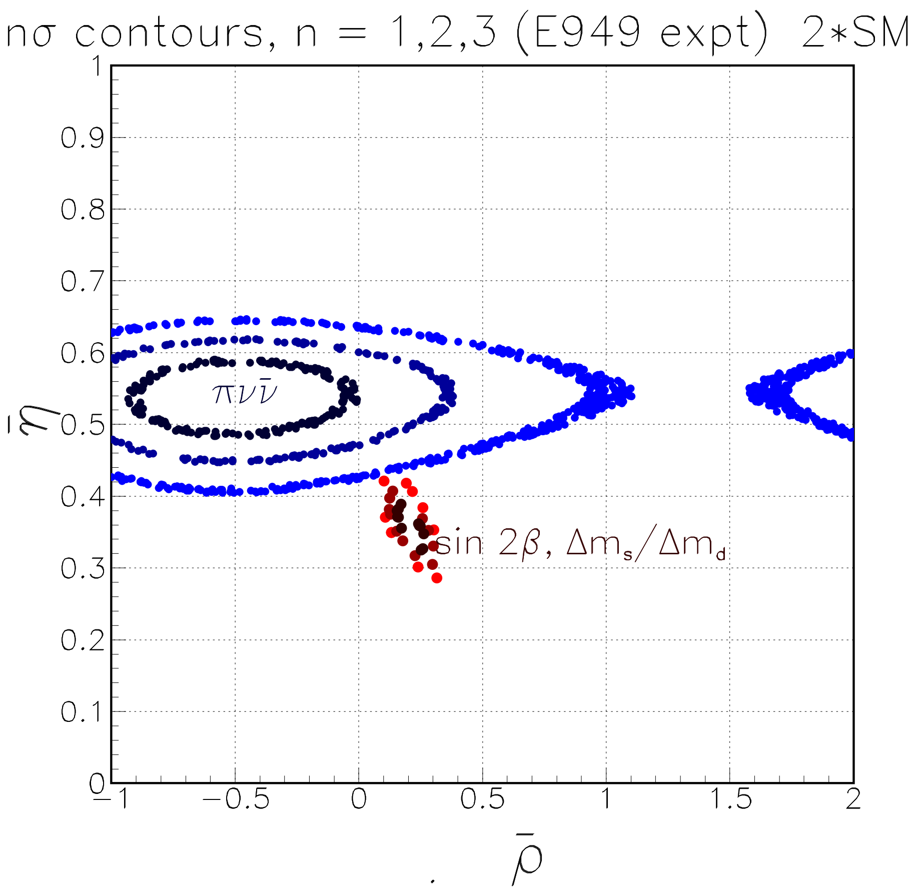


$\Delta\mathcal{B}/\mathcal{B} \approx 20\%$ or

$\Delta\eta/\eta \approx 10\%$ at S/B=2

Process	Events
$K^0_L \to \pi^0\nu\bar{\nu}$ at SM rate	40
$K^0_L \to \pi^0\pi^0$	12.4
$K^0_L \to \pi^\pm e^\mp \nu\gamma$	4.5
$K^0_L \to \pi^-\pi^+\pi^0$	1.7
$K^0_L \to \pi^\pm e^\mp \nu$	0.02
$K^0_L \to \gamma\gamma$	0.02
$\Lambda \to \pi^0 n$	0.01
Interactions ($nN \to \pi^0 X$)	0.2
Accidentals	0.6
Total Background	19.5

Possible impact of E949,KOPIO $\mathrm{K} \to \pi\nu\bar{\nu}$ measurements



Assumptions:

E949 & KOPIO run for approved running period.

$\mathrm{K} \to \pi\nu\bar{\nu}$ rates at twice SM expectation

$\Delta m_s = 17.0 \pm 1.7\ \mathrm{ps}^{-1}$

$\sin 2\beta = 0.70 \pm 0.02$

Summary and outlook for $\mathrm{K} \rightarrow \pi\nu\bar{\nu}$

E949 has observed an additional $\mathrm{K}^+ \rightarrow \pi^+\nu\bar{\nu}$ candidate and measures $\mathcal{B}(\mathrm{K}^+ \rightarrow \pi^+\nu\overline{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10}$ for the combined data of E787 and **E949** (PRL **93**(2004) 31801). The result is consistent with the current Standard Model prediction.

E949 analysis of $\mathrm{K}^+ \rightarrow \pi^+\nu\bar{\nu}$ for momenta $P(\pi^+) < 195$ MeV/c in progress.

E949: Approved (1999), HEP at AGS halted(2002), other funding sources sought...

Another stopped-K^+ experiment to measure $\mathrm{K}^+ \rightarrow \pi^+\nu\bar{\nu}$ under consideration at KEK in Japan. K^+ decay-in-flight experiments under consideration at FNAL and CERN.

E391a: ($\mathrm{K}^0_\mathrm{L} \rightarrow \pi^0\nu\bar{\nu}$ at KEK) Completed first run in June 2004, results early 2005.

KOPIO: Approved by NSF(2003), construction start in 2005, in need of zealous collaborators.

These experiments would be able to test the precise predictions for $\mathbf{K} \rightarrow \boldsymbol{\pi\nu\bar{\nu}}$ branching fractions.

Thanks to G.Isidori, E949 & KOPIO collaborations.

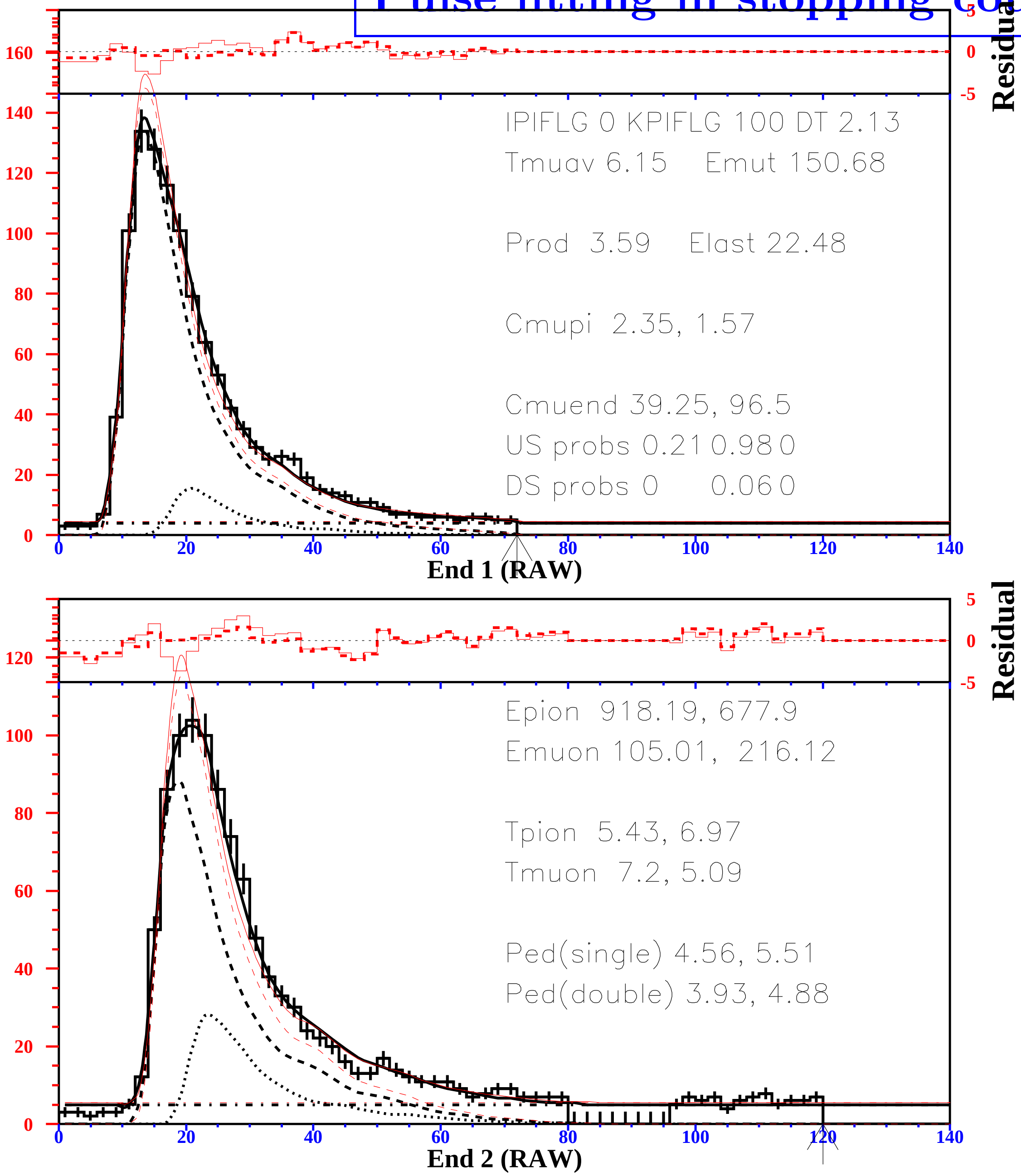
$\boxed{\textbf{Extras}}$

$$\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu}) = K_+ \left(\left[\mathrm{Im}\lambda_t \frac{X}{\lambda^5}\right]^2 + \left[\mathrm{Re}\lambda_c \frac{P_0}{\lambda} + \mathrm{Re}\lambda_t \frac{X}{\lambda^5}\right]^2 \right)$$

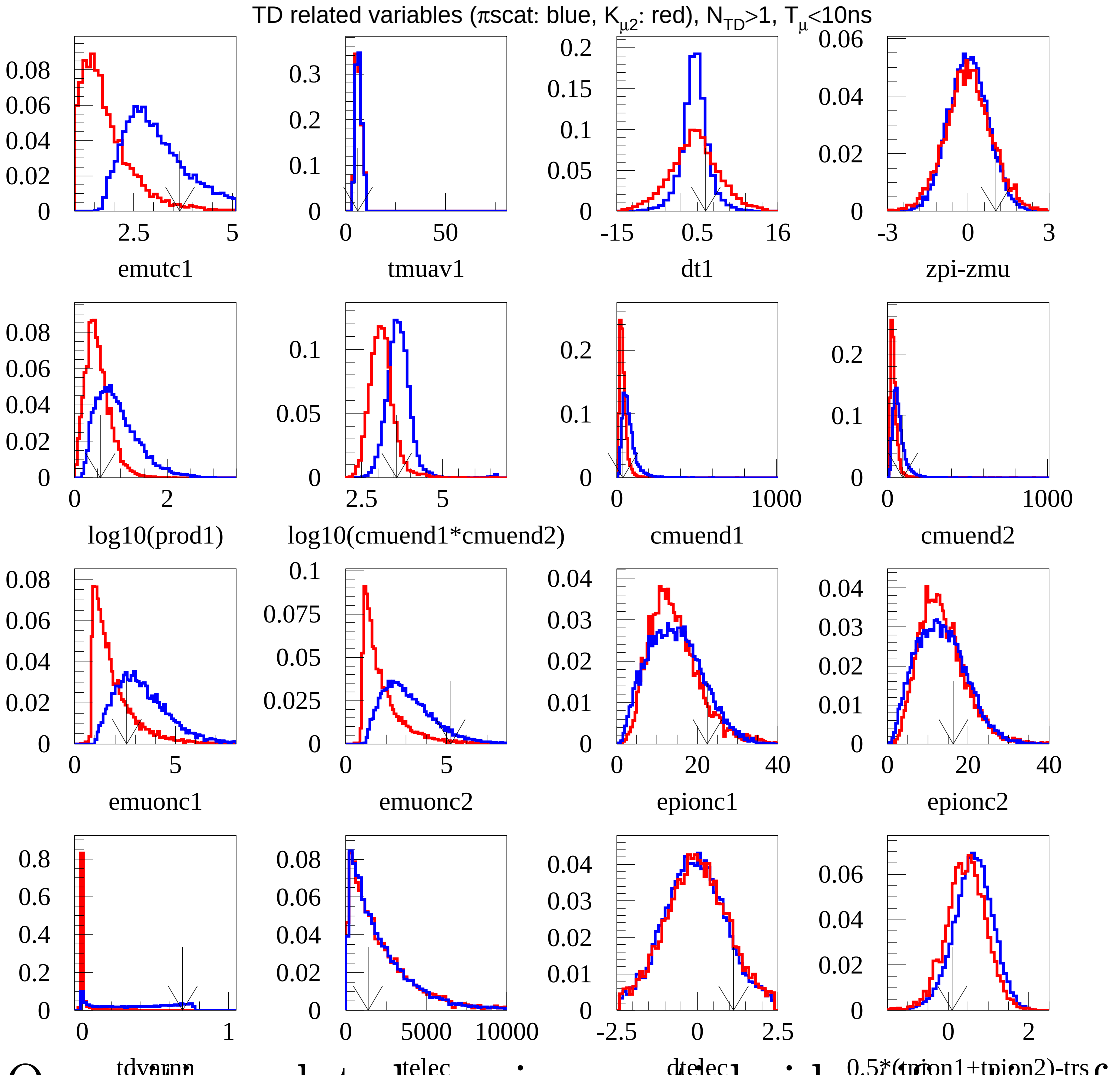
$$\mathcal{B}(\mathrm{K}^0_\mathrm{L} \to \pi^0\nu\bar{\nu}) = K_0 \left(\left[\mathrm{Im}\lambda_t \frac{X}{\lambda^5}\right]^2 \right)$$

$$\begin{aligned}
\lambda_i &\equiv V^*_{is}V_{id} \\
K_+ &\equiv r_+ B \\
K_0 &\equiv r_0 B \tau(\mathrm{K}^0_\mathrm{L})/\tau(\mathrm{K}^+) \\
B &\equiv 3\alpha^2\mathcal{B}(\mathrm{K}^+ \to \pi^0 e^+\nu)/2\pi^2 \sin^4\theta_\mathrm{W} \\
X &\equiv X(x_t) \equiv \tfrac{x_t}{8(x_t-1)}\left(x + 2 + \tfrac{3x-6}{x-1}\ln x\right) \\
x_t &\equiv (m_t/m_W)^2 \\
r_+ &= 0.901 \\
r_0 &= 0.944 \\
P_0 &= 0.40 \pm 0.06 \ (\mathrm{charm})
\end{aligned}$$

Pulse fitting in stopping counter



Compare TD properties of candidate with π^+ and μ^+ samples



Quantities related to pion particle identification from TD variables. Events with similar background rejection and fitted muon time < 10 ns are selected. The pion signal (blue) and the muon background (red) are shown in the same plots. The arrows indicate the positions of the candidate event.

Remind: E949-2002 beam conditions were not optimized

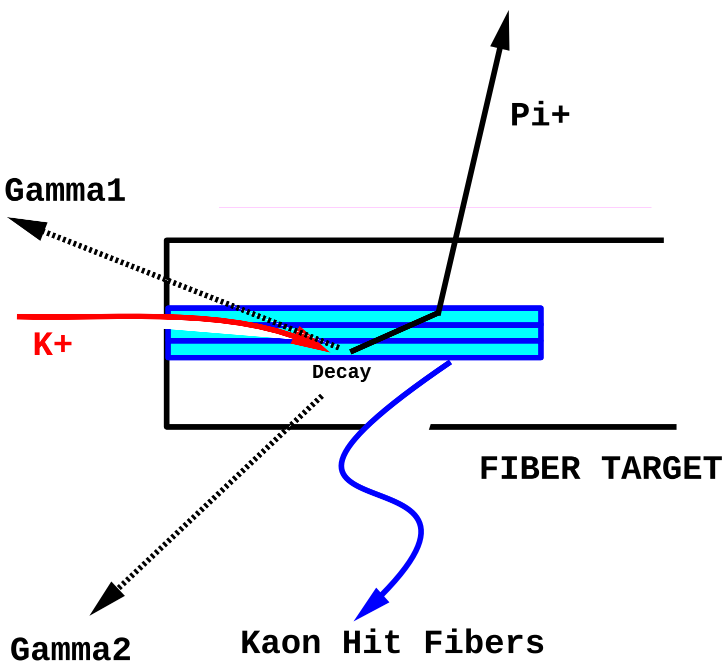
- a faiulre of the AGS power supply
- reduced operating voltage of one of the DC separators
- 12 weeks

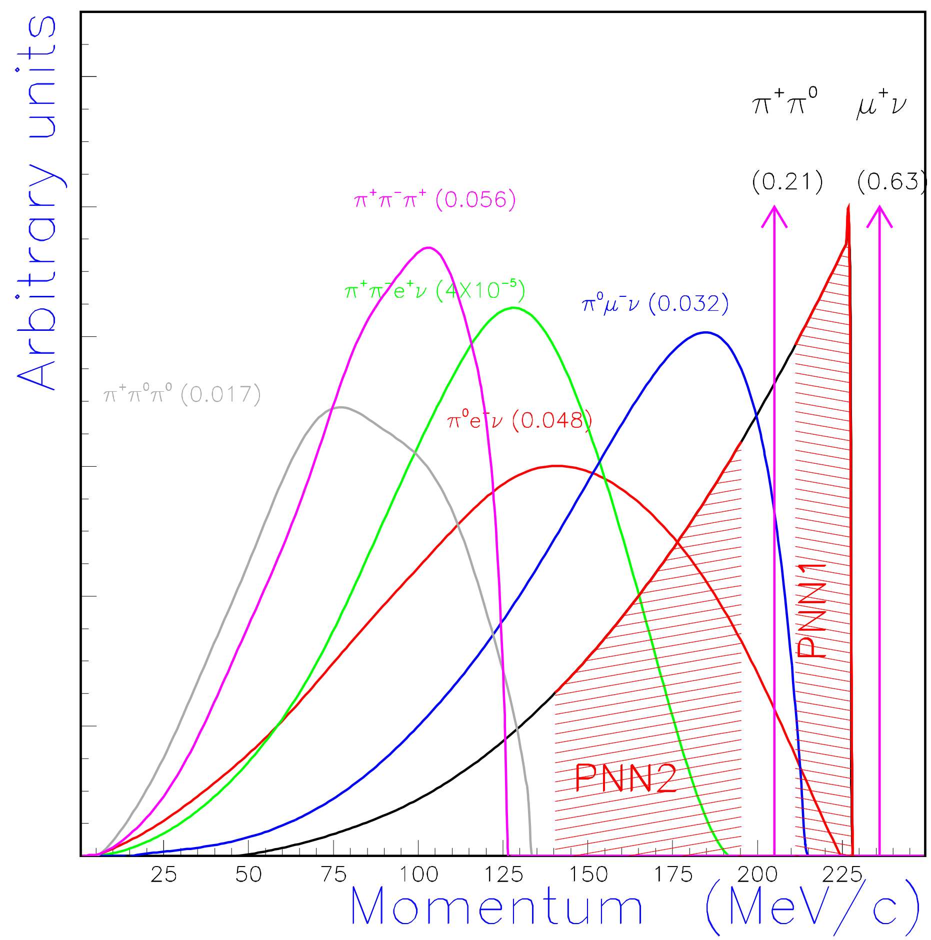
The conditions will be improved in the next run.

		E787	E949-'02	E949 optimized
AGS energy	GeV	24	22	24
beam spill	sec	2.2	2.2	4.1
cycle	sec	4.2	5.4	6.4
duty factor	%	52	41	64
K^+/π^+		4	3	4
N_K in the spill		1.8	2.5	5.0
N_K	MHz	0.8	1.2	1.2
rates in the detector	M		$\times 2$	$\times 2$ or less
beam time	weeks		12	$\geq$60

PNN2: $K^+ \to \pi^+\nu\bar{\nu}$ below $K^+ \to \pi^+\pi^0$ peak

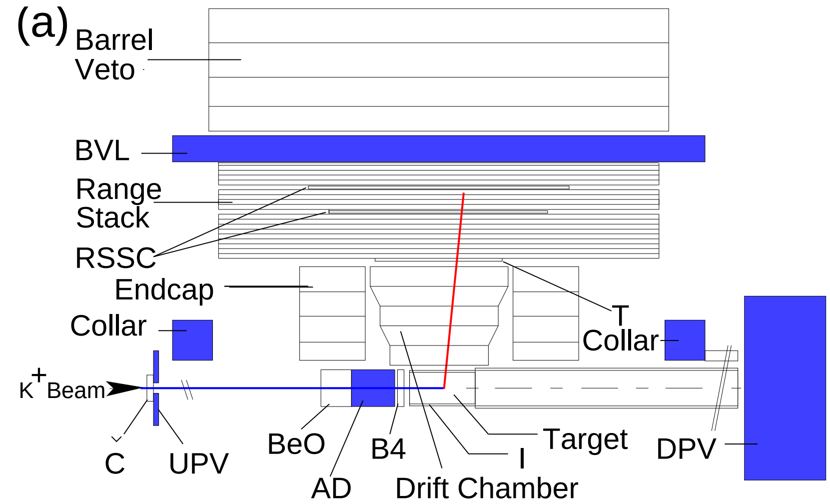
- More phase space than PNN1
- Less loss due to $\pi^+ N$ interactions
- $P(\pi^+) = (140{,}195)$ MeV/c probes more of $K^+ \to \pi^+\nu\bar{\nu}$ spectrum
- Main background mechanism is $K^+ \to \pi^+\pi^0$ followed by π^+ scatter in target.

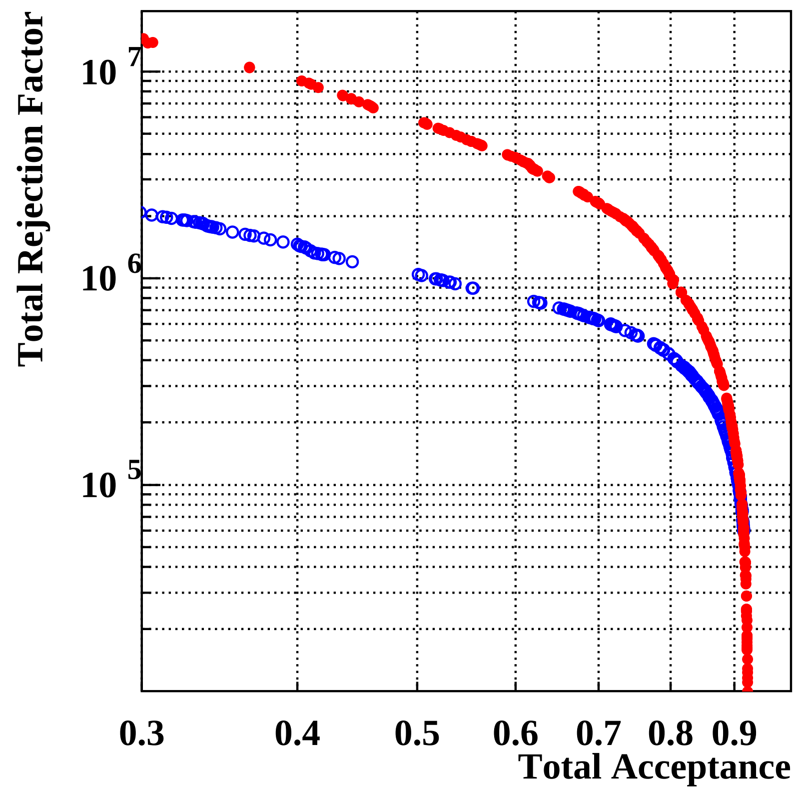




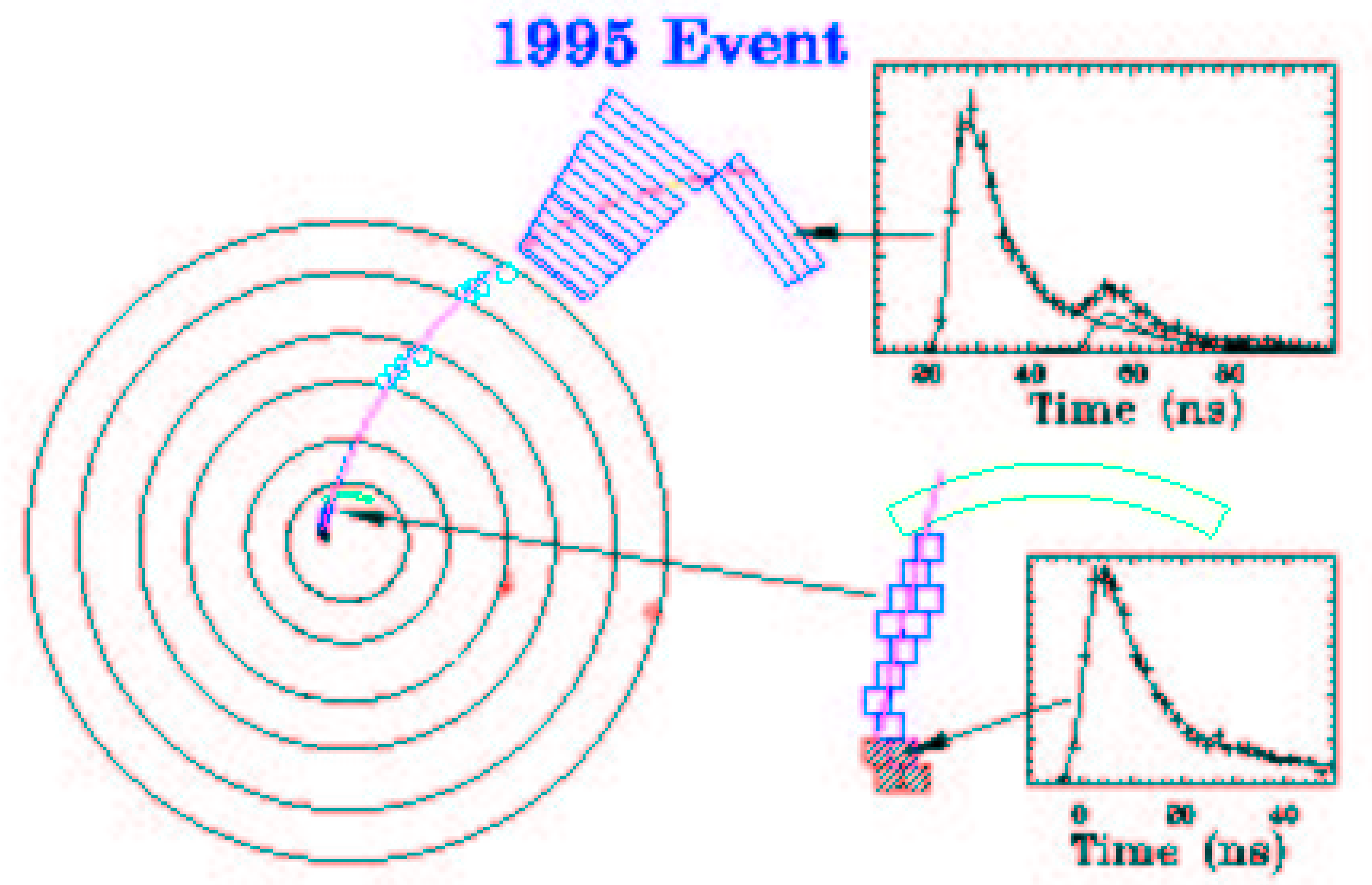
E949 PNN2 analysis

- E787: PNN2 acceptance approx. half PNN1 acceptance
- Goal is equal PNN2 and PNN1 sensitivity with S/B = 1. This implies $\times 2$ increase in acceptance and $\times 5$ increase in background rejection.
- Upgraded photon veto increased PNN1 background rejection. Quantitative assessment of improvement for PNN2 underway.
- Improved algorithms to identify $K^+ \to \pi^+\pi^0$ followed by π^+ scatter in target.

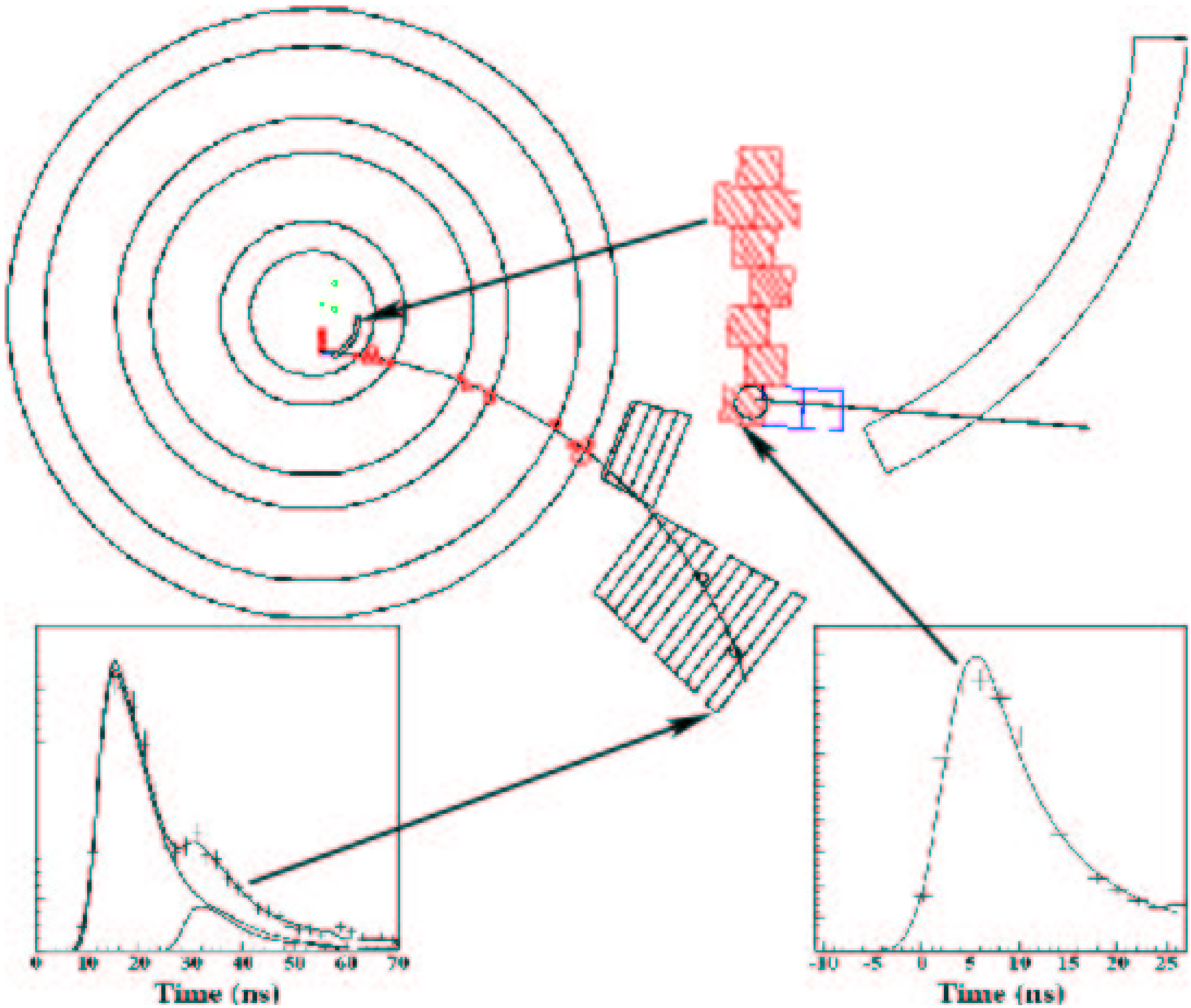


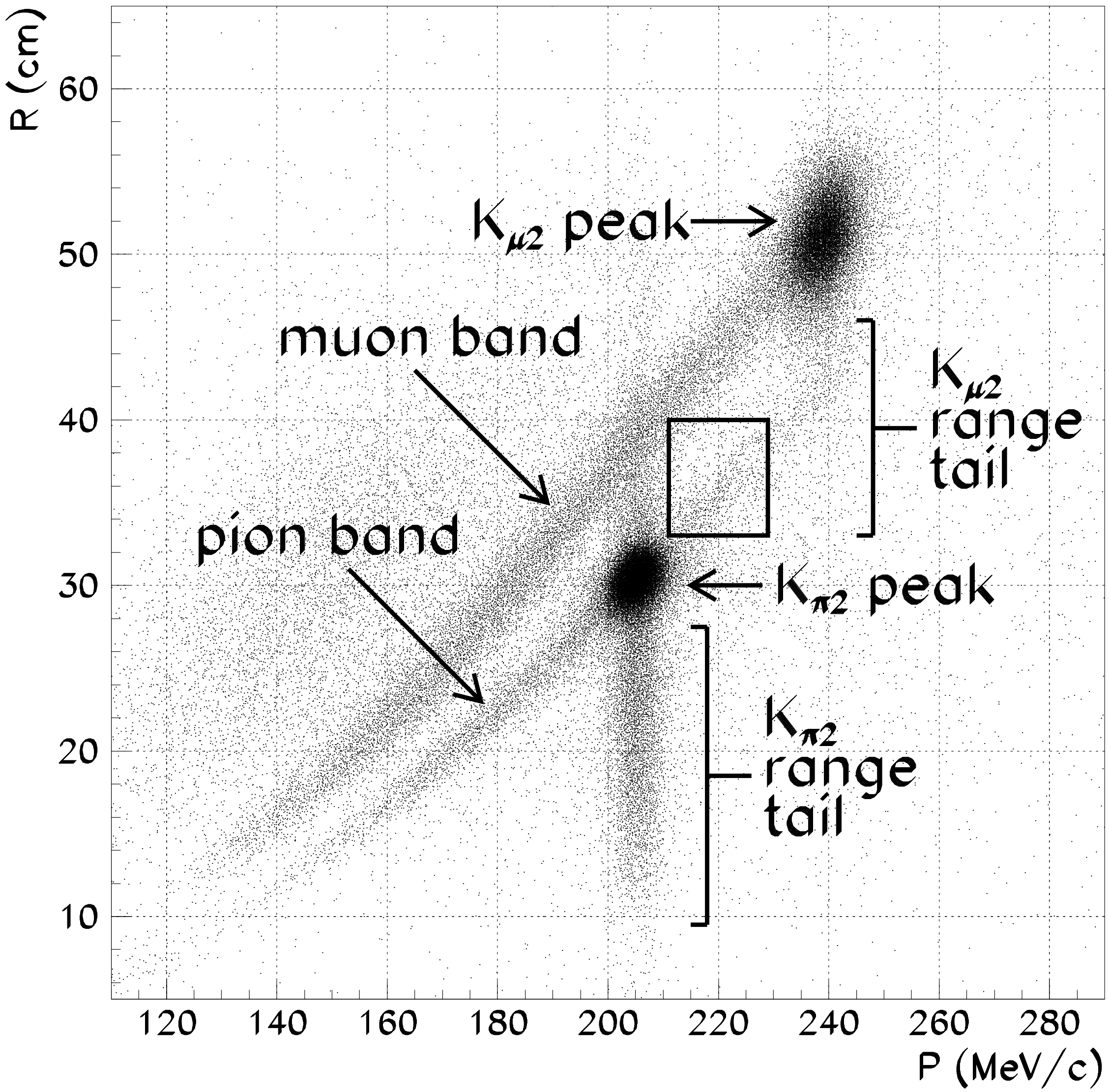


Candidate E787A



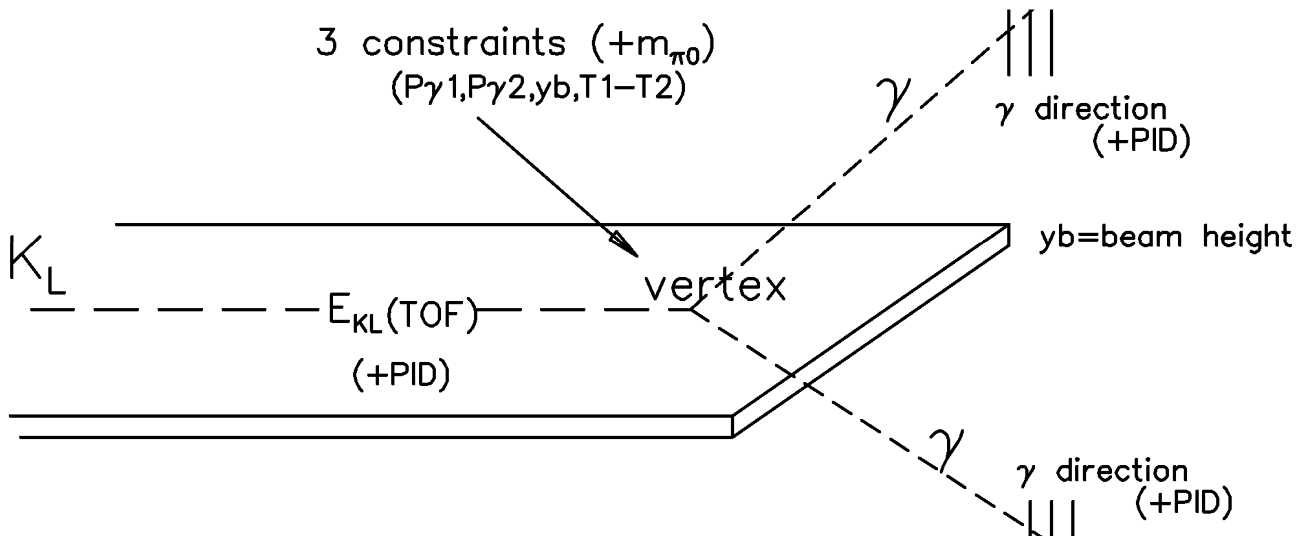
Candidate E787C





E949 Range *vs* Momentum accepted by trigger

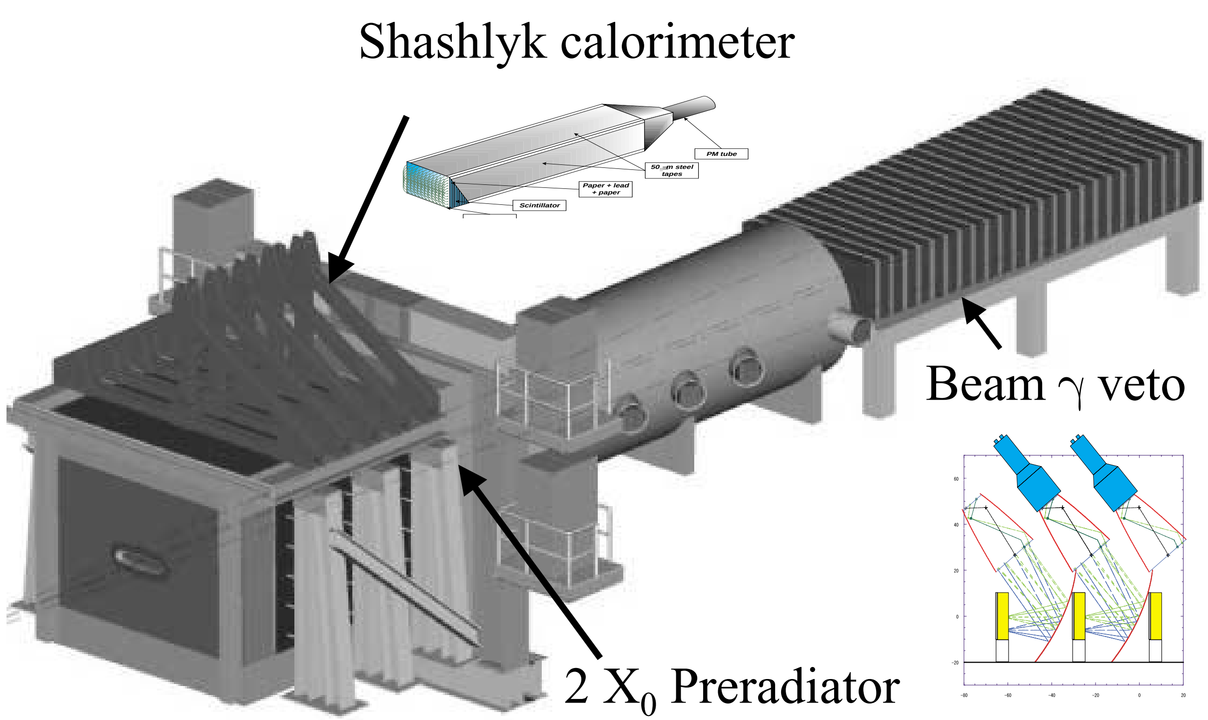
KOPIO Beam and Constraints



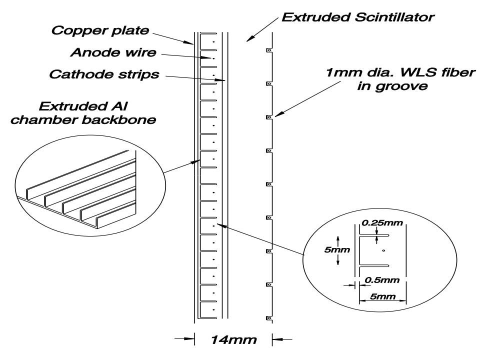
$K_L \rightarrow \pi^0 \nu\bar{\nu}$

(Momentum:TOF) (4π veto)

$\pi^0 \rightarrow \gamma\gamma$ (Energy and direction)

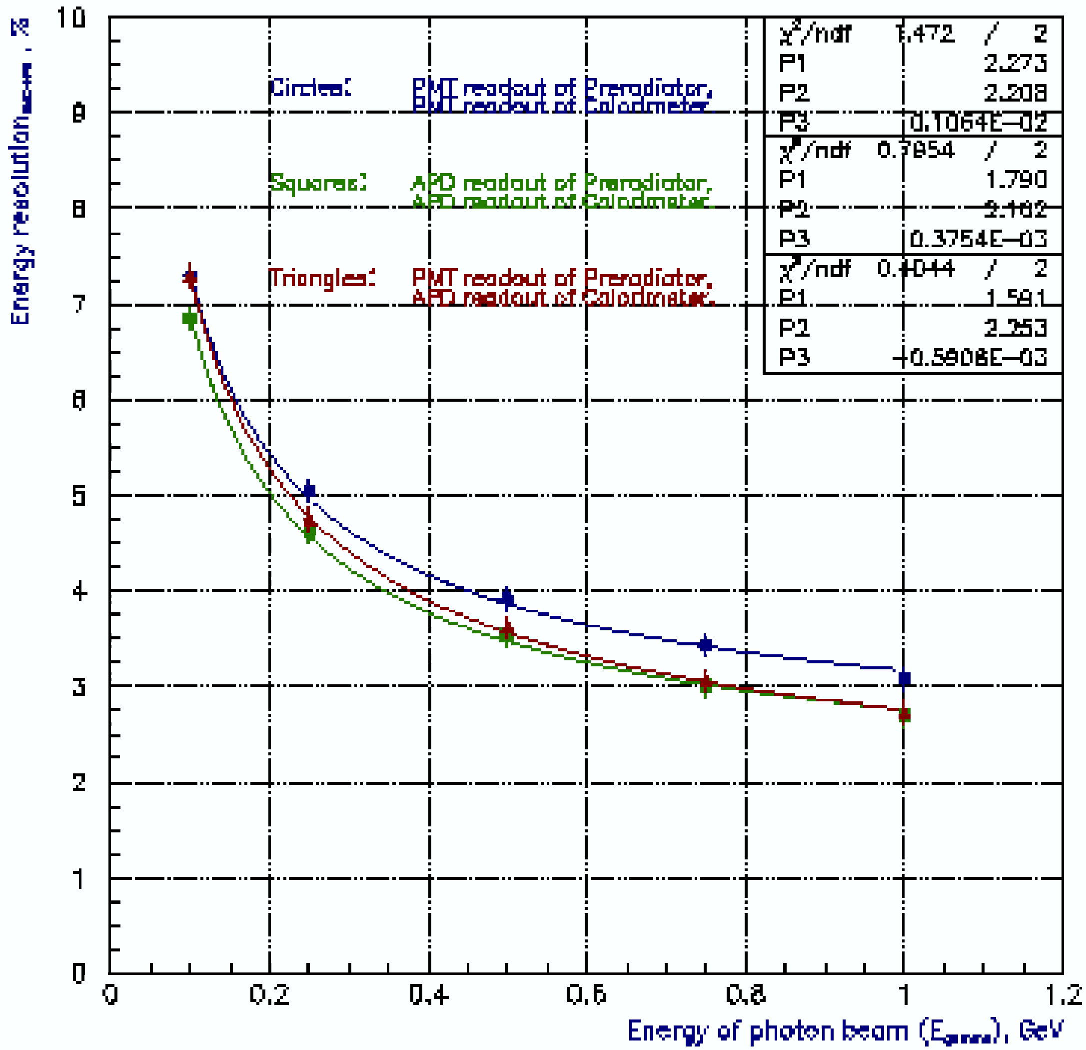


Parameter	Minimal Requirement	Expected Performance
E_γ resolution	$3.5\%/\sqrt{E}$	$2.7\%/\sqrt{E}$
θ_γ resolution (250MeV)	$(25-30)$ mr	23 mr
t_γ resolution	$100ps/\sqrt{E}$	$50ps/\sqrt{E}$
x_γ, y_γ resolution(250MeV)	10mm	$<$ 1mm
μ-bunch width	$300ps$	$200ps$
γ-veto inefficiency	$\bar{\epsilon}_{E787}$	$0.3\bar{\epsilon}_{E787}$



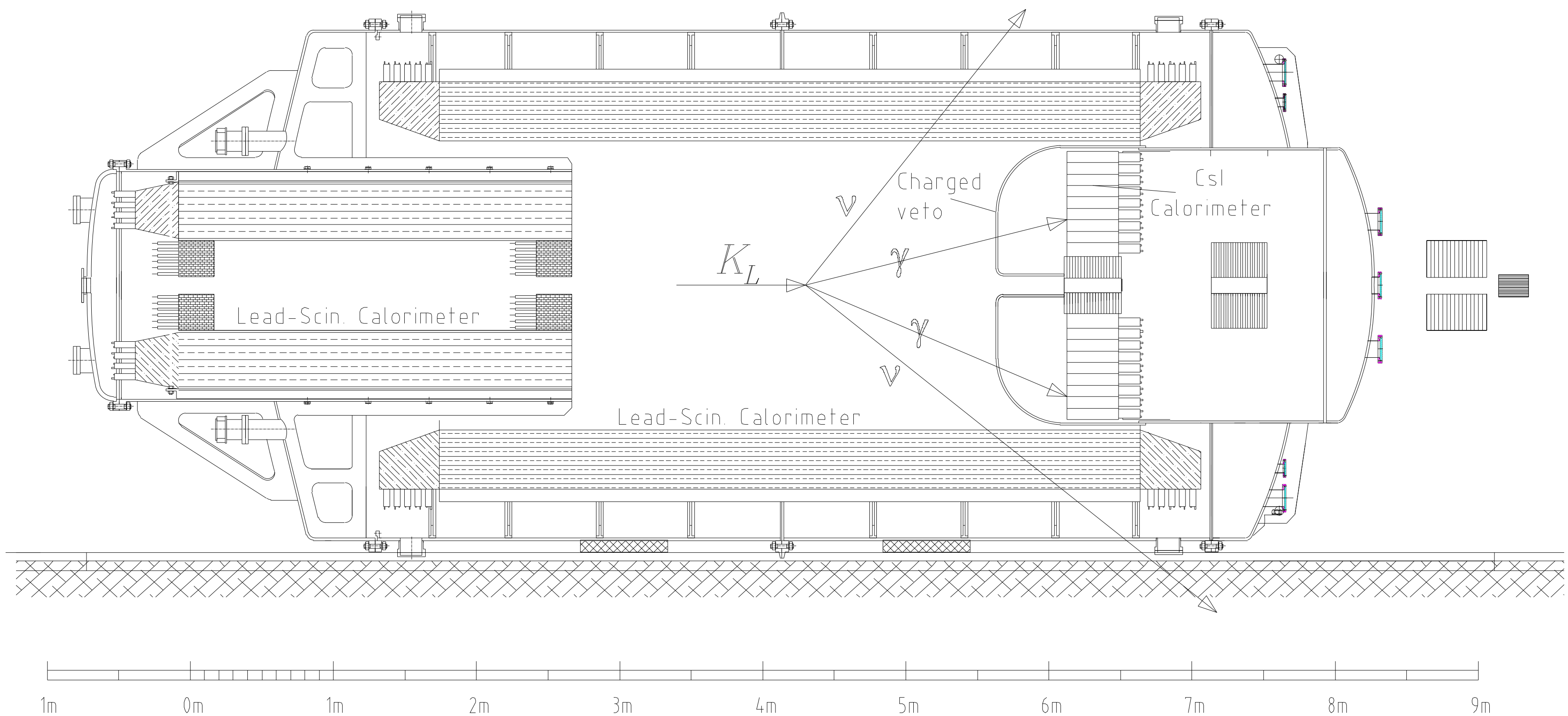
Dav

Simulation: Combined Energy Resolution



$$\sigma \sim \frac{3\%}{\sqrt{E(GeV)}}$$

E391a at KEK


Charged
veto
CsI
Calorimeter
K_L
ν
γ
γ
ν
Lead-Scin. Calorimeter
Lead-Scin. Calorimeter
1m
0m
1m
2m
3m
4m
5m
6m
7m
8m
9m